A HISTORY OF
Technology

Edited by

CHARLES SINGER · E. J. HOLMYARD
A. R. HALL · TREVOR I. WILLIAMS

Assisted by

Y. PEEL *and* J. R. PETTY

Volume III

FROM THE RENAISSANCE TO THE NDUSTRIAL REVOLUTION *c.* 1500–*c.* 1750

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This is the third volume of *A History of Technology*, which is complete in five volumes and covers the subject from the Old Stone Age to the later nineteenth century. It is written in plain language, with few specialist terms, so as to be understood by those with a minimum of technical or scientific training. Very great care has been taken with the illustrations, nearly all of which are specially drawn. Every opportunity is taken of conveying information graphically by maps, charts, and tables.

Details of the other volumes are given on the back of this jacket.

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PREFACE

THIS third volume of *A History of Technology*, unlike its predecessors, can draw upon contemporary printed sources, which, as the centuries advance, constitute a large and rapidly expanding technical literature. Correspondingly, archaeological evidence, prominent in the first two volumes, becomes of less importance, though no doubt much may yet be learnt of the technical practice of the sixteenth and seventeenth centuries from artefacts, from sites of manufacture, and from old equipment. Studies of this kind, for the period of the present volume, are not yet numerous. However, at this stage the wealth of literary evidence for almost every technique of manufacture and production—often very copiously illustrated, as with such classics as Agricola's *De re metallica* (1556) or the great *Encyclopédie* (1751–72) at the limits of our survey—is already so great that it cannot be adequately summarized even in a massive volume. The Editors have therefore necessarily been highly selective in their choice of topics for discussion, and have perforce imposed on authors restrictions of space that have rendered their tasks far from easy. The Editors have sought to emphasize those changing aspects of technology which were of the greatest social and economic importance, while at the same time illustrating the gradual permeation of technological innovation by the results of scientific inquiry.

Without doubt, the greatest occurrence in the history of Europe and of the whole world in the period treated in this volume was the emergence of modern science, with all its fruitful potentialities. The study of this supremely significant movement falls outside the compass of this *History*, but its repercussions will be felt throughout the present volume and its two successors. At the close of the Middle Ages the points of contact between science and technology were few and tenuous: certain aspects of them are discussed in chapters 19 and 22. It fell within the province of the philosopher to explain the phenomena of nature; their use for practical ends was left to the craftsman. The philosopher was much concerned with books and opinions, and but little with things; he displayed admirable intellectual ingenuity in framing his explanations of the natural world in general terms while largely neglecting their application in detail. The craftsman, on the other hand, knew little or nothing beyond trade methods and processes which he followed because they had been handed down to him and because they brought the results he sought; he was altogether innocent of theories to explain his actions. Only in the seventeenth century (though the idea had been adumbrated in the Middle Ages) was it realized—and even then by few—that science and the crafts were alike concerned with natural phenomena and could aid each other. Gradually it was seen that knowledge of nature conferred power to control its forces. From the time of Francis Bacon, Galileo, and Descartes there have always been men in Europe believing that science must ultimately guide the operations of the technician, and that a scientific technology would shape the future course of civilization.

Despite this, it would be absurd to overestimate the effect of such thinking, or of the achievements of pure science, on the technology of Europe in the period covered by this volume. Some few techniques—those of navigation (ch 20) and industrial chemistry (ch 25), for example—were directly modified by the application of scientific ideas, but in relation to many others premature attempts to rationalize and improve craft methods failed dismally. The gradual penetration of scientific method and discovery into the economic activities of production, and the substitution of analysis and precise measurement for the craftsman's impalpable skill, make a very long story extending through the remainder of this work. Until long after the close of the seventeenth century, industrial progress depended overwhelmingly on craft invention rather than on the fruits of systematic scientific research. The complete ascendancy of the latter, from about the end of the nineteenth century, marks a turning-point in human affairs upon which this *History* will conclude. Hence although great achievements were being made in pure science, the basic elements of technology in the sixteenth and seventeenth centuries were not greatly dissimilar from those of earlier times. The dominance of hand-tools and of natural or animal power, a relatively small use of metals, a vast expenditure of skilled and unskilled human effort, and a small scale of production were as characteristic of these centuries as of those immediately preceding them. Even the character of the inventions and new methods of this inventive age was not novel, for the progressive craftsman or entrepreneur continued to play the leading role.

Il n'y a que le premier pas qui coûte. In the perspective of three more centuries of history the apotheoses of long technological traditions regarded as the marvels of the age—the great wooden ships (ch 18), the ponderous machines for raising water (ch 13), the massive stone buildings (ch 10), and the intricately woven tapestries (ch 8)—diminish in importance as compared with the first humble offshoots of scientific research. These, for our period, were the pendulum clock (ch 24), inquiries into the properties of metals (ch 2), and, indeed, the very instruments that science invented to prosecute its own researches (chs 22, 23). The former are, like the dinosaur, unequalled products of a line of evolution doomed to extinction; the latter, heralds of a new course of development whose future is still unguessed. In this volume the Editors have sought to give due attention to both.

It has also been their design in this volume to prepare the way for the discussion of the Industrial Revolution which will be the subject of its immediate successor. Chapters 2, 3, 7, and 17 indicate how firmly the foundations were laid for the great changes in production and economic relations of the second half of the eighteenth century, affecting chiefly the use of metals and coal, the textile industry, and transportation. It will be seen that inventiveness was not ineffective before the times of Abraham Darby (the second), Richard Arkwright, and James Watt; that indeed men had long been conscious of the existence of the problems the solution of which made possible the industrialization first of western Europe, and then of the world.

The geographical limitations of this *History*, and the reasons for adopting them, were set out in the preface to volume II and need not be repeated. Following the design there described, the present volume is wholly concerned with the countries of western Europe. Their history is now doubly unique, since it embraces both the birth of modern science and that of industrialism. The relationship of these states to the Near East and the rest of the globe becomes the opposite of that prevailing previously, to which attention was drawn in the epilogue to volume II. Europe is drawing ever more largely upon the rest of the world for raw materials and primary products (ch 1), exporting manufactured goods in return; and this continent is no longer borrowing from the technical heritage of regions more anciently civilized, but is instead establishing among them its own technical hegemony. It is not within our scope to discuss the economic aspects of this changed relationship, as a result of which, by the end of the nineteenth century, Europe held almost all the rest of the world in commercial fee. Its inevitable impact upon European technology through the new problems of manufacture it created is seen throughout the remainder of the work.

A word of explanation on the wide chronological variation of the chapters in the present volume may be required. It arises from the fusion in Europe at this time of the old technology, mainly of ancient Near Eastern origin, with a newer technology in which the scientific element is in the ascendant. Hence certain topics, which particularly illustrate the latter development, such as cartography and navigation (chs 19, 20) or the construction of scientific instruments (chs 22, 23), have been treated here from antiquity onwards. In other cases, as with the use of hand-tools (ch 5) which have altered little in many centuries, it has been convenient to carry the discussion forward and bring it to a conclusion. The history of techniques fits no simple scheme, and the chronological limits assigned to the volumes of this *History* are to be taken only as broad guides to their contents. The present volume is largely concerned with events of the sixteenth and seventeenth centuries, that is, with the technology of the age between the Italian Renaissance and the Industrial Revolution, but it has often proved convenient and indeed essential to cross these limits in either direction.

As the general history and geography of Europe and North America are generally known, and as sources for further information are readily accessible to all, it has not seemed necessary to include in the present volume such chronological tables and general maps as were given in its predecessors. The time-scale of our volumes diminishes rapidly, as the available material grows proportionately. Volume I had a time-span of geological scale; volume II covered roughly two thousand years; the present volume extends over little more than two hundred. As the time-scale is reduced, so the events of political history are, for the historians of science and technology, diminished in significance. In the period of this volume the city-state waned and the nation-state emerged; religious bigotry gave place to economic rivalry; France replaced Spain as the leading power in Europe. But these events, important in themselves, had little effect on the changes in techniques discussed in these pages. It would be more relevant to turn to economic history, to examine the growing ascendancy of the Atlantic seaboard of Europe over the Mediterranean, to study changes in economic organization and the relations of economic groups, and to inquire into the processes of economic growth. But to attempt such a survey would be to embark upon a complete history of modern industrial civilization, and that is not our object.

The Editors record with regret the death of one of the contributors to this volume, Mr J. F. Flanagan. His chapter on 'Figured Fabrics' was passed by him in galley proof and all the illustrations had received his approval. For assistance in the preparation of this volume, special thanks are due to Professors R. J. Forbes, A. W. Skempton, Cyril S. Smith, and E. G. R. Taylor. All the authors have given generous assistance in the preparation of illustrations.

There have again been changes in the editorial staff. With great regret the Editors accepted the resignation of Dr Elsbeth Jaffé, who wished to be free to complete researches of her own. Her learning, scholarship, and painstaking devotion were freely given to the preparation of the first two volumes of this *History*. Miss M. Reeve has joined the staff. The Editors once more express their thanks to the other members of their team—Mrs A. Clow, Mrs E. Harrison, Mrs D. A. Peel, and Miss J. R. Petty. On them has fallen a heavy burden of bibliographical research and routine work, which has been well and cheerfully borne. The Editors have continued to receive at every point the warm assistance of the staff of the Clarendon Press.

The production of such a work as this would be impossible without recourse to large libraries. The Editors once more tender their thanks to the officials of the British Museum Library, the Cambridge University Library, the London Library, the Patent Office Library, the Science Library, and the Warburg Institute. In the present volume, artists' work has been less essential than in its predecessors; the greater part of it has again been entrusted to Mr D. E. Woodall, but we are also glad to acknowledge the services of Mr E. Norman and Mr F. Janca. The indexes have been compiled by Miss M. A. Hennings.

The financial outlay necessary for the completion of this *History* has proved considerably greater than was originally anticipated. The Editors wish to acknowledge the beneficent generosity of Imperial Chemical Industries Limited in making renewed provision for this purpose, by which the completion of the work is ensured. In particular they again thank Mr W. J. Worboys for his unfailing interest, support, and encouragement.

CHARLES SINGER
E. J. HOLMYARD
A. R. HALL
TREVOR I. WILLIAMS

CONTENTS

ILLUSTRATIONS xv

LIST OF ABBREVIATIONS xxxv

PART I

PRIMARY PRODUCTION

1. FOOD AND DRINK by R. J. FORBES, Professor of History of Pure and Applied Sciences in Antiquity, University of Amsterdam 1

2. METALLURGY AND ASSAYING by CYRIL STANLEY SMITH, Professor of Metallurgy, University of Chicago, and R. J. FORBES 27

3. COAL MINING AND UTILIZATION by J. U. NEF, Professor of Economic History, University of Chicago 72

4. WINDMILLS by REX WAILES 89

PART II

MANUFACTURE

5. TRADESMEN'S TOOLS *c*1500–1850 by R. A. SALAMAN 110

with *A Note on the Wheelwright's Trade* by J. GERAINT JENKINS and R. A. SALAMAN 123
and *A Note on Coopering* by J. GERAINT JENKINS and R. A. SALAMAN 128

6. FARM-TOOLS, VEHICLES, AND HARNESS 1500–1900 by OLGA BEAUMONT, Assistant, Museum of English Rural Life, University of Reading, and J. GERAINT JENKINS, Assistant Keeper, Museum of English Rural Life, University of Reading 134

7. SPINNING AND WEAVING by R. PATTERSON, Curator, Castle Museum, York 151

with *A Note on Knitting and Knitted Fabrics* by JAMES NORBURY, Chief Designer, Patons and Baldwins 181

8. FIGURED FABRICS by the late J. F. FLANAGAN 187

9. GLASS by R. J. CHARLESTON, Assistant Keeper, Department of Ceramics and Glass, Victoria and Albert Museum, London, and L. M. ANGUS-BUTTERWORTH, Director, The Newton Heath Glass Works, Manchester 206

PART III

MATERIAL CIVILIZATION

10. BUILDING CONSTRUCTION by MARTIN S. BRIGGS 245

11. TOWN-PLANNING FROM THE ANCIENT WORLD TO THE RENAISSANCE by MARTIN S. BRIGGS 269

12. LAND DRAINAGE AND RECLAMATION by L. E. HARRIS 300

13. MACHINES AND MECHANISMS by A. P. USHER, Emeritus Professor of Economics, Harvard University 324

14. MILITARY TECHNOLOGY by A. R. HALL 347

15. PRINTING by MICHAEL CLAPHAM, Metals Division, Imperial Chemical Industries 377

with *A Note on Technical Advances in the Manufacture of Paper before the Nineteenth Century* by JOHN OVERTON, Thomas Nelson and Sons Ltd, Publishers 411

PART IV

COMMUNICATIONS

16. BRIDGES by S. B. HAMILTON, O.B.E., Building Research Station, Watford 417

17. CANALS AND RIVER NAVIGATIONS BEFORE 1750 by A. W. SKEMPTON, Professor of Civil Engineering, University of London 438

18. SHIPS AND SHIPBUILDING by G. P. B. NAISH, Assistant Keeper, National Maritime Museum, Greenwich 471

19. CARTOGRAPHY, SURVEY, AND NAVIGATION TO 1400 by CHARLES SINGER, DEREK J. PRICE, and E. G. R. TAYLOR 501

20. CARTOGRAPHY, SURVEY, AND NAVIGATION 1400–1750 by E. G. R. TAYLOR, Emeritus Professor of Geography, University of London 530

PART V

APPROACH TO SCIENCE

21. THE CALENDAR by SIR HAROLD SPENCER JONES, K.B.E., Astronomer Royal 1933–55 558

22. PRECISION INSTRUMENTS TO 1500 by DEREK J. PRICE 582

with a section (VII) on Hero's instruments by A. G. DRACHMANN

23. THE MANUFACTURE OF SCIENTIFIC INSTRUMENTS FROM *c*1500 TO *c*1700 by DEREK J. PRICE 620

24. MECHANICAL TIMEKEEPERS by H. ALAN LLOYD, M.B.E. 648

25. INVENTION IN CHEMICAL INDUSTRIES by F. W. GIBBS, Assistant Secretary, The Royal Institute of Chemistry, London 676

EPILOGUE

THE RISE OF THE WEST by A. R. HALL 709

INDEXES 723

PLATES *at end*

ILLUSTRATIONS

Metallurgical furnaces used for smelting silver. Left, *charging a furnace, while red-hot metal flows from its base.* Right, *removing litharge flowing down the hearth-wall with a crochet. The furnaces correspond to Agricola's descriptions (1556); the long white smocks were presumably worn for protection against the heat. From a painting of 1521, by Hans Hesse, on the 'Miners' Altar' in the church of St Anne, Annaberg, in the Erzgebirge district of Saxony. Annaberg was an important silver-mining settlement early in the sixteenth century.* Reproduced by courtesy of the Gewerkschaft Eisenhütte Westfalia, Wethmar, Post Lünen FRONTISPIECE

TEXT-FIGURES*

1. FOOD AND DRINK *by* R. J. FORBES

1 *The potato plant.* From J. GERARD. 'The Herball or Generall Historie of Plantes', p. 781. London, 1597 2
2 *The sweet potato.* From J. GERARD. *Ibid.*, p. 780 3
3 *Maize.* From L. FUCHS. *De historia stirpium commentarii*, p. 825. Basel, 1542 4
4 *West Indian sugar-factory.* From P. POMET. 'Histoire générale des drogues', p. 94. Paris, 1694 7
5 *The tobacco plant.* From P. PENA and M. DE L'OBEL. *Stirpium adversaria nova*, p. 252. Antwerp, 1570 8
6 *Botanic Garden in Paris.* From G. DE LA BROSSE. 'Description du jardin des plantes medicinales estably par le Roy Louis le Juste, à Paris', Pl. facing p. 8. Paris, 1636 9
7 *Distilling-apparatus.* (Above) *Brick-built still.* From C. ESTIENNE. 'L'Agriculture et maison rustique', p. 171. Paris, 1567. (Below) *Cask still.* From J. FRENCH. 'The Art of Distillation', p. 29. London, 1651 10
8 *von Weigel's still.* After C. E. VON WEIGEL. *Observationes chemicae et mineralogicae*, Pt II, Pl. I. Göttingen, 1773. D. E. Woodall 11
9 *The hop-garden.* From R. SCOT. 'A perfite platform of a Hoppe Garden', pp. 23, 30. London, 1574 14
10 *Ramelli's portable iron roller-mill.* After RAMELLI. 'Le diverse et artificiose machine', fig. 129. Paris, 1588. D. E. Woodall 16
11 *Böckler's roller-mill.* From G. A. BÖCKLER. *Theatrum machinarum novum*, Pl. I. Cologne, 1662 17
12 *Verantius's mechanical bolting-device.* From VERANTIUS. *Machinae novae*, fig. 28. Venice [1620 ?] 18
13 *Water-driven corn-mill.* From RAMELLI. 'Le diverse et artificiose machine', fig. 119. Paris, 1588 19
14 *Cooking-spit.* From G. A. BÖCKLER. *Theatrum machinarum novum*, Pl. LXXXII. Cologne, 1662 21

2. METALLURGY AND ASSAYING *by* CYRIL STANLEY SMITH and R. J. FORBES

15 *Brass-foundry.* From L. ERCKER. 'Beschreibung allerfürnemsten Mineralischen Ertzt- und Berckwercksarten', fol. 112^{v}. Prague, 1574 38
16 *Bronze gun-foundry.* From P. SURIREY DE SAINT RÉMY. 'Mémoires d'artillerie', Vol. 2, Pl. CXXXII. Paris, 1697 39
17 *Bell-founding.* From BIRINGUCCIO. 'De la Pirotechnia', p. 98. Venice, 1540 40
18 *Pouring molten lead.* From S. DE CAUS. 'Les raisons des forces mouvantes' (2nd ed.), Book 3: "De la fabrique des orgues", p. 6. Paris, 1624 45
19 (Foreground) *Rolling-mill*; (background) *draw-plate.* From J. A. PANTHEUS. *Voarchadumia contra alchimiam*, fol. 24^{v}. Paris, 1550 47
20 *Blast-furnaces.* From AGRICOLA. *De re metallica*, p. 313. Basel, 1556 49
21 *Italian smelting-furnaces.* From M. A. DELLA FRATTA ET MONTALBANO. *Practica minerale*, p. 90. Bologna, 1678 50

* The names at the end of entries are those of the artists who drew the illustrations.

22 *Furnaces for reducing copper.* From L. ERCKER. 'Beschreibung allerfürnemsten Mineralischen Ertzt- und Berckwercksarten', fig. facing p. 118. Prague, 1574 51
23 *Wind-furnace.* From BIRINGUCCIO. 'De la Pirotechnia', fol. 106. Venice, 1540 51
24 *Wind- and blast-furnaces.* From L. ERCKER. 'Beschreibung allerfürnemsten Mineralischen Ertzt- und Berckwercksarten', fol. 97^v. Prague, 1574 52
25 *Arrangement for melting metal in a casting-ladle.* From BIRINGUCCIO. 'De la Pirotechnia', fol. 105^v. Venice, 1540 52
26 *Stationary melting-hearths.* From BIRINGUCCIO. *Ibid.*, fol. 105 53
27 *Furnaces for the crucible-assay of copper ores.* From L. ERCKER. 'Beschreibung allerfürnemsten Mineralischen Ertzt- und Berckwercksarten', fol. 98^v. Prague, 1574 53
28 *The* trompe. From M. A. DELLA FRATTA ET MONTALBANO. *Practica minerale*, fig. facing p. 146. Bologna, 1678 54
29 *Self-stoking furnace.* From L. ERCKER. 'Beschreibung allerfürnemsten Mineralischen Ertzt- und Berckwercksarten', fol. 82^v. Prague, 1574 55
30 *Ring of coals.* From L. ERCKER. *Ibid.*, fol. 80^r 56
31 *Exterior view of reverberatory furnace.* From BIRINGUCCIO. 'De la Pirotechnia', fol. 104. Venice, 1540 57
32 *Assay-laboratory.* From BIRINGUCCIO. *Ibid.*, fol. 47 58
33 *Assay-laboratory with furnaces.* From L. ERCKER. 'Beschreibung allerfürnemsten Mineralischen Ertzt- und Berckwercksarten', title page. Prague, 1574 59
34 *Forge-fire.* From AGRICOLA. *De re metallica*, p. 180. Basel, 1556 60
35 *Side and rear views of muffle.* From 'Bergwerck und Probierbüchlin', p. 27. Frankfurt a. M., 1533 60
36 *Mould and screw-press.* From L. ERCKER. 'Beschreibung allerfürnemsten Mineralischen Ertzt- und Berckwercksarten', fol. 84^r. Prague, 1574 61
37 *Assayers' glassware and pottery vessels.* From L. ERCKER. *Ibid.*, fol. 65^v 62
38 *Moulding cupels by hand.* From BIRINGUCCIO. 'De la Pirotechnia', fol. 46. Venice, 1540 63
39 *Parting-flask and annealing cups.* After J. ARPHE. 'Quiltador de la Plata, oro, y Piedras', p. 25. Valladolid, 1572. D. E. Woodall 65
40 *Four types of furnace.* From L. ERCKER. 'Beschreibung allerfürnemsten Mineralischen Ertzt- und Berckwercksarten', fol. 70^v. Prague, 1574 66
41 *Assay-laboratory.* From L. ERCKER. *Ibid.*, fol. 63^v 67
TAILPIECE. *General view of a French ironworks.* From LE MARQUIS DE COURTIVRON and E. J. BOUCHU. "Art des forges et fourneaux à fer" in 'Descriptions des arts et métiers faites ou approvées par Messieurs de l'Académie Royale des Sciences', Vol. 19, section 3, Pl. II. Paris, 1762 71

3. COAL MINING AND UTILIZATION *by* J. U. NEF

42 *Coal-mine.* From J. MORAND. "L'Art d'exploiter les mines de charbon de terre" in 'Descriptions des arts et métiers faites ou approvées par Messieurs de l'Académie Royale des Sciences', Vol. 3, Pt II, Pl. XVII. Paris, 1773 75
43 *Portion of a map.* After R. GARDINER. 'Englands Grievance Discovered, in relation to the Coal-Trade', map. London, 1655. D. E. Woodall 76
44 *Coke-burning.* After J. MORAND. "L'Art d'exploiter les mines de charbon de terre" in 'Descriptions des arts et métiers faites ou approvées par Messieurs de l'Académie Royale des Sciences', Vol. 3, Pt II, Pl. XXXV. Paris, 1773. D. E. Woodall 80
45 *Horse-whim haulage machine.* From J. MORAND. *Ibid.*, Vol. 3, Pt II, Pl. XXXIV, no. 1 82
46 *Horse-tram.* After J. MORAND. *Ibid.*, Vol. 3, Pt II, Pl. XXXIV, no. 3. D. E. Woodall 84
TAILPIECE. *Miners and seamen.* From E. BOWEN. 'Royal English Atlas', cartouche from map of Northumberland. London, [*c* 1760] 88

4. WINDMILLS *by* REX WAILES

47 *Corn-grinding tower-mill.* From RAMELLI. 'Le diverse et artificiose machine', fig. 132. Paris, 1588 90

48 *Corn-grinding post-mill.* From RAMELLI. *Ibid.*, fig. 133 91

49 *Post-mill.* From D. DIDEROT and J. LE R. D'ALEMBERT (Eds). 'Encyclopédie', Planches: Vol. I, "Agriculture, économie rustique", Pl. IV. Paris, 1762 92

50 *Russian sunk post-mill.* After photograph by courtesy of the Polytechnic Museum, Moscow. D. E. Woodall 93

51 *Weatherboarded post-mill.* After photograph by courtesy of Mr Rex Wailes. D. E. Woodall 94

52 *Octagonal timber smock-mill.* After photograph by courtesy of Mr Rex Wailes. D. E. Woodall 95

53 *Brick tower-mill.* After photograph by courtesy of Mr Rex Wailes. D. E. Woodall 96

54 *Raised* petit-pied *mill.* After photograph by courtesy of Mr Rex Wailes. D. E. Woodall 97

55 *Russian post-mill.* After photograph by courtesy of the Polytechnic Museum, Moscow. D. E. Woodall 98

56 *A sail.* After photograph by courtesy of Mr Rex Wailes. D. E. Woodall 101

57 *Tower-mill with annular sail.* After photograph by courtesy of Mr Rex Wailes. D. E. Woodall 102

58 *View and partial section of underdrift millstones and gear.* (Right) *Early cylindrical bolter.* From D. DIDEROT and J. LE R. D'ALEMBERT (Eds). 'Encyclopédie', Planches: Vol. I, "Agriculture, économie rustique", Pl. V. Paris, 1762 105

59 *Section of a* paltrok *saw-mill.* After L. VAN NATRUS, J. POLLY, and C. VAN VUUREN. 'Groot Volkomen Moolenboek', Vol. I, Pl. V. Amsterdam, 1734. D. E. Woodall 107

5. TRADESMEN'S TOOLS *by* R. A. SALAMAN

60 *Comparison of Roman and modern tools.* From R. A. SALAMAN. *Woodworker*, **59**, 165, 1955. London, The Woodworker. Drawings by Jack Laird 111

61 *Examples of home-made tools.* Drawings by Jack Laird 112

62 (A) *Farrier's shoeing pincers*; (B) *coach-maker's pistol-router*; (C) *wheelwright's post tire-bender.* Drawings by Jack Laird 113

63 *Smith's beam-drill.* From 'Guide to the West Yorkshire Folk Museum' (2nd ed.) by F. ATKINSON. Halifax Museums, 1954 114

64 *Adzes.* Drawings by Jack Laird 117

65 *Wooden braces.* Drawings by Jack Laird 118

66 *Side-axes.* Drawings by Jack Laird 118

67 (A) *Bruzz*; (B) *croze*; (C) *nogg*; (D) *froe*; (E) *shipwright's caulking mallet.* Drawings by Jack Laird 119

68 (A) *Wing calipers*; (B) *stop-chamfering.* Drawings by Jack Laird 120

69 (A) *Watch-maker's pin-vice*; (B) *spring calipers.* Drawings by Jack Laird 120

70 (A) *Draw-knife*; (B) *trenching-plane.* Drawings by Jack Laird 121

71 *Wheelwright's workshop.* After line engraving by Stanley Anderson. D. E. Woodall 125

72 *Coopering.* After line engraving by Stanley Anderson. D. E. Woodall 131

6. FARM-TOOLS, VEHICLES, AND HARNESS, 1500–1900 *by* OLGA BEAUMONT and J. GERAINT JENKINS

73 *A selection of seventeenth-century farm tools.* From G. MARKHAM. 'Farewell to Husbandry'. London, 1620 135

74 *Breast-plough.* After photograph by courtesy of the University of Reading Museum of English Rural Life. D. E. Woodall 135

75 *Drainage-tools.* From W. BLITH. 'The English Improver Improved', Pl. facing p. 66. London, 1652 136

76 (Right) *Dibbler*; (left above) *sickle*; (left below) *bill-hook.* After photographs by courtesy of the University of Reading Museum of English Rural Life. D. E. Woodall 137

77 *A nineteenth-century harvest scene.* From 'Sketches of Rural Affairs', p. 182. London, 1848 138

78 *Barley-awner.* After photograph by courtesy of the University of Reading Museum of English Rural Life. D. E. Woodall 139

79 *Hand-barrow.* After photograph by permission of the National Museum of Wales. D. E. Woodall 139
80 *Dorsal-car.* After photograph by permission of the National Museum of Wales. D. E. Woodall 140
81 *Slide-car.* After photograph by permission of the National Museum of Wales. D. E. Woodall 141
82 *Scotch cart.* After A. YOUNG. 'General View of the Agriculture of Essex', Vol. I, Pl. XXXVIII. London, 1807. D. E. Woodall 142
83 *Tumbril.* After photograph by courtesy of the University of Reading Museum of English Rural Life. D. E. Woodall 143
84 *Box-wagon.* After photograph by courtesy of the University of Reading Museum of English Rural Life. D. E. Woodall 146
85 *Bow-wagon.* After photograph by courtesy of the University of Reading Museum of English Rural Life. D. E. Woodall 147
86 *Two cart-horses.* From photograph by courtesy of the University of Reading Museum of English Rural Life 148
TAILPIECE. *Jethro Tull's hoe-plough.* After J. T[ULL]. 'The Horse-Hoing Husbandry' (2nd ed.), Pl. VI. London, 1733. D. E. Woodall 150

7. SPINNING AND WEAVING *by* R. PATTERSON

87 *Carding wool.* After A. N. PLUCHE. 'La spectacle de la nature', Vol. 6, Pl. VII. Paris, 1762. D. E. Woodall 153
88 *Lewis Paul's rectangular carding machine.* From 'Wool Research 1918–1948', Vol. 4: 'Carding', fig. 1. Leeds, Wool Industries Research Association, 1948 154
89 *Paul's revolving carding machine.* From *ibid.*, fig. 2 154
90 *Bourn's carding machine.* From *ibid.*, fig. 3 155
91 *Combing wool.* From 'Encyclopédie Méthodique', Vol. 6, Recueil de Planches, Pl. II. Paris, Liége, 1786 155
92 *Flax-working.* From photograph of an engraving by D. CHODOWIECKI, by courtesy of CIBA Limited, Basel 156
93 *Flax-breaking machine.* From A. GRAY. 'A Treatise on Spinning Machinery', Pl. II, fig. 3. Edinburgh, 1819 157
94 *Dutch fining-mill.* From J. HORNER. 'The Linen Trade of Europe during the Spinning-Wheel Period', fig. 36. Belfast, McCaw, Stevenson and Orr, 1920 158
95 *Low Irish spinning-wheel.* From J. HORNER. *Ibid.*, fig. 11 160
96 *English spinning-wheel.* From J. HORNER. *Ibid.*, fig. 14 161
97 *Irish castle-wheel.* From J. HORNER. *Ibid.*, fig. 12 162
98 *Lewis Paul's spinning-machine.* From E. BAINES. 'History of the Cotton Manufacture in Great Britain', p. 139, fig. 4. London, 1835 163
99 *Warping-mill.* From A. N. PLUCHE. 'La spectacle de la nature', Vol. 6, Pl. IX. Paris, 1762 164
100 *Loom invented by Claude Dangon.* After C. RAZY. 'Étude analytique des petits modèles de métiers', Pl. I. Lyons, Rey, 1913. D. E. Woodall 165
101 *Bouchon's mechanism.* From A. BARLOW. 'The History and Principles of Weaving by Hand and Power', fig. 127. London, 1878 166
102 *Dutch ribbon-loom.* From A. BARLOW. *Ibid.*, fig. 248 167
103 *Shuttle-mechanism.* After A. BARLOW. *Ibid.*, figs 252, 253. D. E. Woodall 168
104 *Rack-and-pinion shuttle.* After A. BARLOW. *Ibid.*, figs 254, 255. D. E. Woodall 168
105 *M. de Gennes's 'New Engin'.* From *Phil. Trans.*, no. 140, sole figure, 1678 169
106 *Kay's flying shuttle.* From R. GUEST. 'A Compendious History of the Cotton Manufacture', Pl. IV. Manchester, 1823 170
107 *Raising the nap.* From D. DIDEROT and J. LE R. D'ALEMBERT (Eds). 'Encyclopédie', Planches: Vol. 3, "Draperie", Pl. VII, fig. 24. Paris, 1763 171

108 *Leonardo's gig-mill.* From A. P. USHER. 'History of Mechanical Inventions', fig. 95. Cambridge, Mass., Harvard University Press, 1954 172
109 *Gig-mill.* From V. ZONCA. 'Novo Teatro di Machine et Edificii', p. 96. Padua, 1621 173
110 *Shearmen at work.* After E. MUMMENHOFF. 'Der Handwerker in der deutschen Vergangenheit', fig. 78. Leipzig, Diederichs, 1901. D. E. Woodall 174
111 *Cropping-shears.* From D. DIDEROT and J. LE R. D'ALEMBERT (Eds). 'Encyclopédie', Planches: Vol. 3, "Draperie", Pl. VIII, fig. 29. Paris, 1763 175
112 *Leonardo's shearing-machine.* From T. BECK. *Z. Ver dtsch. Ing.*, **50**, 648, fig. 137, 1906. Düsseldorf, V.D.I. Verlag 175
113 *Frizing-mill.* From D. DIDEROT and J. LE R. D'ALEMBERT (Eds). 'Encyclopédie', Planches: Vol. 3, "Draperie", Pl. X, fig. 1. Paris, 1763 176
114 *Linen-press.* From 'Encyclopédie Méthodique', Vol. 6, Recueil de Planches, Pl. II, fig. 14. Paris, 1786 177
115 *A calender.* From A. N. PLUCHE. 'La spectacle de la nature', Vol. 6, Pl. XVII. Paris, 1762 177
116 *Simple method of making* sprang. After frame 3 of the filmstrip 'The Story of Knitting.' London, International Wool Secretariat. D. E. Woodall 182
117 *Plaited* sprang. After frame 4 of the filmstrip 'The Story of Knitting.' London, International Wool Secretariat. D. E. Woodall 183
118 *Arab sandal-sock.* London, Victoria and Albert Museum. After photograph; Crown copyright reserved. D. E. Woodall 184
119 *Knitting on a rectangular frame.* After frame 8 of the filmstrip 'The Story of Knitting.' London, International Wool Secretariat. D. E. Woodall 184
120 *Knitting on a circular frame.* After frame 7 of the filmstrip 'The Story of Knitting.' London, International Wool Secretariat. D. E. Woodall 185
121 *A simple knitting-stick.* Drawing from the original in the Museum of Patons and Baldwins Limited. D. E. Woodall 186
122 *Tudor cap.* London, Victoria and Albert Museum. After photograph; Crown copyright reserved. D. E. Woodall 186

8. FIGURED FABRICS *by* J. F. FLANAGAN

123 *Diagrams showing plan of warp and healds.* After diagram by J. F. Flanagan. D. E. Woodall 188
124 *The principles of the figure-harness with neck.* After diagram by J. F. Flanagan. D. E. Woodall 189
125 *Probable arrangement of the figure-harness without neck.* Diagram by J. F. Flanagan 190
126 *Chinese draw-loom.* London, Victoria and Albert Museum, drawing. After photograph; Crown copyright reserved. D. E. Woodall 191
127 *Methods of lifting and depressing healds.* After sketch by J. F. Flanagan. D. E. Woodall 192
128 *Method of 'redding'.* Diagram by J. F. Flanagan 193
129 *Weft-faced figured-tabby weave.* Diagram by J. F. Flanagan 194
130 *Weft-faced figured-twill weave.* Diagram by J. F. Flanagan 195
131 *Early tabby tissue.* Diagram by J. F. Flanagan 197
132 Diasprum *weave.* Diagram by J. F. Flanagan 198
133 *Warp effect twill-ground tissue.* Diagram by J. F. Flanagan 199
134 *Fourteenth-century Italian twill-ground tissue.* Diagram by J. F. Flanagan 199
135 *Satin ground-tissue.* Diagram by J. F. Flanagan 200
136 *Silk fragments from Kerch.* London, British Museum, Greek and Roman Department. Diagram by J. F. Flanagan 201
137 *Four-end twill damask.* Diagram by J. F. Flanagan 202
138 *Five-end satin damask.* Diagram by J. F. Flanagan 203
139 *Figured velvet.* Diagram by J. F. Flanagan 204

9. GLASS *by* R. J. CHARLESTON and L. M. ANGUS-BUTTERWORTH

140 *General view of a glass-furnace.* AGRICOLA. *De re metallica* (Eng. trans. by H. C. HOOVER and LOU H. HOOVER from ed. of 1556), p. 589. London, Mining Magazine, 1912. From photograph by courtesy of the Director of the Science Museum, South Kensington, London 209

141 *The calcar.* From D. DIDEROT and J. LE R. D'ALEMBERT (Eds). 'Encyclopédie', Planches: Vol. 10, "Verrerie en bois", Pl. XV. Paris, 1772 211

142 *The second furnace.* AGRICOLA. *De re metallica* (Eng. trans. by H. C. HOOVER and LOU H. HOOVER from ed. of 1556), p. 588. London, Mining Magazine, 1912. From photograph by courtesy of the Director of the Science Museum, South Kensington, London 212

143 *Agricola's second glass-furnace.* AGRICOLA. *Ibid.*, p. 591. London, Mining Magazine, 1912. From photograph by courtesy of the Director of the Science Museum, South Kensington, London 213

144 *Interior of a French glass-house.* After D. DIDEROT and J. LE R. D'ALEMBERT (Eds). 'Encyclopédie', Planches: Vol. 10, "Verrerie en bois", Pl. I. Paris, 1772. D. E. Woodall 214

145 *Plan of the glass-house.* After D. DIDEROT and J. LE R. D'ALEMBERT (Eds). *Ibid.*, Planches: Vol. 10, "Verrerie en bois", Pl. III. D. E. Woodall 215

146 *Glassworker's chair and tools.* After D. DIDEROT and J. LE R. D'ALEMBERT (Eds). *Ibid.*, Planches: Vol. 10, "Verrerie en bois", Pl. XVII. D. E. Woodall 219

147 *Stages in making a wine-glass.* From D. DIDEROT and J. LE R. D'ALEMBERT (Eds). *Ibid.*, Planches: Vol. 10, "Verrerie en bois", Pl. XX 220

148 *View and plan of bottle-glass works.* After photograph by courtesy of Aktiebolaget Faglavihs Glesbruk, Göteborg. D. E. Woodall 222

149 *Plan of bottle-glass works.* After photograph by courtesy of Aktiebolaget Faglavihs Glesbruk, Göteborg. D. E. Woodall 223

150 *Detail from a trade-card.* After photograph of a trade card in the collection of Sir Ambrose Heal. D. E. Woodall 225

151 *The English type of glass-house cone.* From D. DIDEROT and J. LE R. D'ALEMBERT (Eds). 'Encyclopédie', Planches: Vol. 10, "Verrerie angloise", Pl. III. Paris, 1772 227

152 *Plan of English-type glass-house.* From D. DIDEROT and J. LE R. D'ALEMBERT (Eds). *Ibid.*, Planches: Vol. 10, "Verrerie angloise", Pl. II 228

153 *Section through* 'Zwischengoldglas'. Diagram by R. J. Charleston 229

154 *Spectacle-maker's shop.* From HARTMAN SCHOPPER. *Panoplia*, Sig. K. 4. Frankfurt a. M., 1568 231

155 *One of Newton's proposed machines.* From A. R. HALL. *Ann. Sci.*, **11**, 41, fig. 14, 1955. London, British Society for the History of Science 232

156 *Machine for shaping forms.* From PÈRE CHERUBIN D'ORLÉANS. 'La dioptrique oculaire', fig. 51. Paris, 1671 235

157 *Huygens's lens-figuring equipment.* From SOCIÉTÉ HOLLANDAISE DES SCIENCES. 'Œuvres complètes de Christiaan Huygens', Vol. 22, pp. 299, 302. The Hague, Nijhoff, 1932 236

TAILPIECE. *An astronomical telescope.* From J. HEVELIUS. *Machina coelestis*, fig. Y. Danzig, 1673. 244

10. BUILDING CONSTRUCTION *by* MARTIN S. BRIGGS

158 *Italian Renaissance dome-construction.* Drawing by M. S. Briggs 246

159 *Renaissance masonry.* Based on J. DURM. 'Handbuch der Architektur', Vol. 2, Pt V: 'Die Baukunst der Renaissance in Italien', fig. 138. Stuttgart, Kröner, 1903. M. S. Briggs 247

160 *Italian vaulted or 'coved' ceiling.* After F. A. CHOISY. 'Histoire de l'architecture', Vol. 2, p. 652, figs 3A, 3B. Paris, Gauthier-Villars, 1899. M. S. Briggs 248

161 *Renaissance carpentry.* (Left) *Centring for the main arches.* After CARLO FONTANA. *Templum Vaticanum*, Bk V, Pl. on p. 413. Rome, 1694. M. S. Briggs. (Right) *Roof of the Church of Santa Maria dei Miracoli.* Based on J. DURM. 'Handbuch der Architektur', Vol. 2, Pt V: 'Die Baukunst der Renaissance in Italien', fig. 80. Stuttgart, Kroner, 1903. M. S. Briggs 249

162 *Renaissance carpentry.* After F. A. CHOISY. 'Histoire de l'architecture', Vol. 2, p. 637, fig. 12B; p. 627, fig. 3. Paris, Gauthier-Villars, 1899. M. S. Briggs 250

163 *Mansard roofs.* After F. C. WEBBER. 'Carpentry and Joinery', pp. 153–4. London, Methuen, 1898. M. S. Briggs 252

164 *Design for curved roof-timbers.* After PHILIBERT DE L'ORME. 'Nouvelles inventions pour bien bastir', p. 18. Paris, 1561. M. S. Briggs 253

165 *French Renaissance dome-construction.* After J. F. BLONDEL. 'L'Architecture française', Vol. 2, Pt III, Pl. XIV, fig. 4, Pl. XI, fig. 5; Vol. 1, Pt II, Pl. I, fig. 7. Paris, 1752–6. M. S. Briggs 255

166 *St Paul's Cathedral.* Drawing by M. S. Briggs 259

167 *Construction of stone mullions.* Drawing by M. S. Briggs 260

168 *Details of English masonry.* (A) *Method of sawing.* After SIR (EDWARD) GUY DAWBER. 'Old Cottages, Farmhouses and other Stone Buildings in the Cotswold District', fig. 60. London, Batsford, 1905. (B) *Yorkshire stone finial*; (C) *the same.* (A–C) M. S. Briggs 260

169 *Brick chimney.* Drawing by M. S. Briggs 261

170 *English half-timber construction.* (Left) *The framing of the main timbers.* Drawing by M. S. Briggs. (Right) *The intervals.* After T. GARNER and A. STRATTON. 'The Domestic Architecture of England during the Tudor Period' (2nd ed.), fig. 341. London, Batsford, 1929. M. S. Briggs 262

171 *English half-timber construction.* Drawing by M. S. Briggs 263

172 *Roof-construction.* Drawing by M. S. Briggs 263

173 *Hammer-beam roof.* After A. W. N. PUGIN. 'Specimens of Gothic Architecture', Vol. 2, Pl. VIII. London, 1821. M. S. Briggs 264

174 *Design for the composite roof-trusses.* After R. P[LOT]. 'The Natural History of Oxfordshire', table XIV, fig. 3. Oxford, 1677; and SIR CHRISTOPHER WREN. *Parentalia* (ed. by C. WREN), figs. 4, 5, facing p. 334. London, 1750. M. S. Briggs 265

175 *Chichester Cathedral spire.* After J. ELMES. 'Memoir of the Life and Works of Sir C. Wren', Pl. facing p. 486. London, 1823. M. S. Briggs 265

176 *English wall-panelling.* Drawing by M. S. Briggs 266

TAILPIECE. *Stone-masons.* From HANS SACHS. 'Eigentliche Beschreibung alle Stände . . . mit kunstreichen Figuren [by Jost Amman]', fol. Z. ii. Frankfurt a. M., 1568 268

11. TOWN-PLANNING FROM THE ANCIENT WORLD TO THE RENAISSANCE *by* MARTIN S. BRIGGS

177 *Sketch-plan of ancient Babylon.* After E. UNGER. 'Babylon', Pl. II. Berlin, De Gruyter, 1931. M. S. Briggs 270

178. *Sketch-plan of the Piraeus.* Drawing by M. S. Briggs 271

179 *Sketch-plan of Miletos.* Based on R. E. WYCHERLEY. 'How the Greeks built Cities', Pl. VI [reproduced from A. VON GERKAN. 'Griechische Städteanlagen', Pl. VI. Berlin, De Gruyter, 1924]. London, Macmillan, 1949. M. S. Briggs 272

180 *Sketch-plan of Olynthos.* Based on R. E. WYCHERLEY. *Ibid.*, fig. 4 [reproduced from D. M. ROBINSON. 'Excavations at Olynthus', no. xii, Pls CCLXXI, CCLXXII. Baltimore, Johns Hopkins Press, 1946]. London, Macmillan, 1949. M. S. Briggs 273

181 *Sketch-plan of Priene.* Based on W. B. DINSMORE. 'Architecture of Ancient Greece' (3rd ed.), fig. 96 [reproduced from A. VON GERKAN 'Griechische Städteanlagen', Pl. IX. Berlin, De Gruyter, 1924]. London, Batsford, 1950. M. S. Briggs 274

182 *Sketch-plan of Imperial Rome.* Drawing by M. S. Briggs 276

183 *Plan of Roman fort.* After R.G. COLLINGWOOD. 'Roman Britain', p. 26. Oxford, Clarendon Press, 1923. M. S. Briggs 277

184 *Plan of Silchester.* Based on T. H. HUGHES and E. A. G. LAMBORN. 'Towns and Town Planning, Ancient and Modern', fig. 5. Oxford, Clarendon Press, 1923. M. S. Briggs 277

185 *Plan of Verulamium.* Drawing by M. S. Briggs 278

186 *Sketch-plan of Roman London.* Drawing by M. S. Briggs 278

187 *Sketch-plan of Byzantium.* After A. VAN MILLINGEN. 'Byzantine Constantinople', fig. facing p. 19. London, Murray, 1899. M. S. Briggs 279

188 *Sketch-plan of Timgad.* After A. BALLU. 'Les Ruines de Timgad', fig. facing p. 2. Paris, Neurdein, 1911. M. S. Briggs 280

189 *Sketch-plan of Roman Ostia.* After G. CALZA. 'Gli Scavi di Ostia' (2nd ed.), pp. 2–3. Rome, Libreria dello Stato, 1949. M. S. Briggs 281

190 *Plan of Monpazier.* After T. H. HUGHES and E. A. G. LAMBORN. 'Towns and Town Planning', fig. 17. Oxford, Clarendon Press, 1923. M. S. Briggs 282

191 *Plan of Carcassonne.* Drawing by M. S. Briggs 283

192 *Sketch-plan of Winchelsea.* After T. H. HUGHES and E. A. G. LAMBORN. 'Towns and Town Planning', fig. 45. Oxford, Clarendon Press, 1923. M. S. Briggs 284

193 *Sketch-plan of Neubrandenburg.* Drawing by M. S. Briggs 285

194 *Plan of central Turin.* Drawing by M. S. Briggs 287

195 *Sketch-plan of central Rome.* Drawing by M. S. Briggs 288

196 *Vitry-le-François.* Drawing by M. S. Briggs 289

197 *Plan of Charleville.* Drawing by M. S. Briggs 290

198 *Sketch-plan of the town (Richelieu).* Drawing by M. S. Briggs 292

199 *Amsterdam c 1670.* Drawing by M. S. Briggs 295

200 *Plan of the City of London.* After the engraving by W. HOLLAR. 1669. M. S. Briggs 296

201 *Wren's plan.* Drawing by M. S. Briggs 297

12. LAND DRAINAGE AND RECLAMATION *by* L. E. HARRIS

202 *North Holland.* After R. H. A. COOLS. 'Strijd om de Grond in het Lage Nederland', p. 121. Rotterdam, Nijgh and Van Ditmar, 1948. D. E. Woodall 302

203 *An original drawing by Simon Stevin.* The Hague, State Archives. From S. STEVIN, Patent, 28 November 1589, sub. 9 304

204 *A* tjasker *mill.* After H. A. M. C. DIBBITS. 'Nederland-Waterland een historisch-technisch overzicht', fig. 112. Utrecht, Oosthoek, 1950. D. E. Woodall 305

205 *Drawing by Leeghwater.* After J. A. LEEGHWATER. Archives of the Waterschap 'De Beemster', Purmerend. D. E. Woodall 306

206 *Leeghwater's original plan.* Rijnland 'Loogheemradschap.' After photograph by courtesy of Koninklijke Nederlandse Akademie van Wetenschappen, Amsterdam. D. E. Woodall 307

207 *G. B. Falda's map.* From C. J. MEIJER. 'L'Arte de restituire à Roma la tralasciata navigatione del suo Tevere', Pt III: "Del modo di secare le Palude Pontine". Rome, 1683 313

208 *The construction of* krebbingen. From C. J. MEIJER. 'L'Arte di rendire i fiumi navigabili'. Rome, 1683 314

209 *The Great or Bedford Level.* Cambridge, University Library. Map of 1724 by T. BADESLADE. After photograph by courtesy of the Syndics. D. E. Woodall 316

210 (Left) *Vertical windmill*; (right) *fixed horizontal windmill.* From W. BLITH. 'The English Improver Improved', Pl. facing p. 56. London, 1652 321

TAILPIECE. *An early surveying level.* Cambridge, Whipple Museum of the History of Science. Drawing from the original by permission of the University of Cambridge. D. E. Woodall 323

13. MACHINES AND MECHANISMS *by* A. P. USHER

211 *Agricola's gear-operated pump.* From AGRICOLA. *De re metallica*, p. 131. Basel, 1556 325

212 *Agricola's water-driven ore-crusher.* From AGRICOLA. *Ibid.*, p. 234 327

213 *Besson's improved vertical water-mill.* From J. BESSON. 'Theatre des instrumens', fig. 28. Lyons, 1579 328

214 *Agricola's simple suction-pump.* From AGRICOLA. *De re metallica*, p. 135. Basel, 1556 329

215 *Ramelli's quadruple suction-pump.* From RAMELLI. 'Le diverse et artificiose machine', fig. 5. Paris, 1588 331

216 *Machine for raising water.* From B. FOREST DE BELIDOR. 'Architecture hydraulique', Vol. 2, Pt. I, Pl. III, figs 5, 6. Paris, 1739 333

217 *Besson's screw-cutting lathe.* From J. BESSON. 'Theatre des instrumens', fig. 9. Lyons, 1579 334

218 *Turning an iron mandrel.* From C. PLUMIER. 'L'Art de tourner en perfection', Pl. II, fig. 2. Lyons, 1701 335

219 *Cutting the screw.* From C. PLUMIER. *Ibid.*, Pl. III, fig. 1 336

220 *The mandrel lathe complete.* From C. PLUMIER. *Ibid.*, Pl. XII 337

221 *Steel screws.* After W. TREUE. 'Kulturgeschichte der Schraube', pp. 4, 128, 130. Munich, Bruckmann, 1955. D. E. Woodall 338

222 *Diagrammatic reconstruction of Cellini's screw-press.* Reconstructed from B. CELLINI. 'Opere', Vol. 3, pp. 109–11. Milan, 1811. D. E. Woodall 339

223 *Balance coining-press.* Paris, Hôtel des Monnaies. After photograph. D. E. Woodall 340

14. MILITARY TECHNOLOGY *by* A. R. HALL

224 *Sixteenth-century armourer's workshop.* From STRADANUS (JAN VAN DER STRAET). *Nova reperta*, Pl. XVII. [Antwerp, 1600?] 351

225 *Early sixteenth-century armourer's workshop.* Vienna, Staatsbibliothek, Cod. pal. 3033. From A. SCHULTZ. *Jb. Kunsthist.*, **6**, 109, fol. 184*b*, 1887 352

226 *Soldiers aboard a fighting-galley.* From ROBERTO VALTURIO. *De re militari*, p. clxxxvi^v. Verona, 1472 353

227 *Gun-locks* (*diagrammatic*). After sketch by the author. D. E. Woodall 354

228 *Steps in forging a gun-barrel.* After D. DIDEROT and J. LE R. D'ALEMBERT (Eds). 'Encyclopédie', Planches: Vol. 12, "Fabrique des armes", Pl. I. Paris, 1777. D. E. Woodall 357

229 (Above) *Machinery for boring gun-barrels*; (below) *plan view of one boring-bench.* From D. DIDEROT and J. LE R. D'ALEMBERT (Eds). *Ibid.*, Pls II, III 359

230 *Late fifteenth-century gun-carriage.* From T. H. BOSSERT and W. F. STORCK (Eds). 'Das Mittelalterliche Hausbuch', Pl. LXIX. Leipzig, Seeman, 1912 362

231 *Section and plan of furnace.* Cambridge University Library, MS. AD. 2883: DIEGO DE PRADO Y TOVAR. 'Encyclopaedia de Fundicion de Artilleria y su platica manuel', fols 5^v, 6^r. 1603. After photographs by courtesy of the Syndics. D. E. Woodall 363

232 *Making moulds for cannon.* Cambridge University Library, MS. AD. 2883: DIEGO DE PRADO Y TOVAR. *Ibid.*, fols 3^r, 36^v, 37^v. From photographs by courtesy of the Syndics 364

233 *Machine-saw.* Cambridge University Library, MS. AD. 2883: DIEGO DE PRADO Y TOVAR. *Ibid.*, fol. 49^r. From photograph by courtesy of the Syndics 365

234 *Sixteenth-century bronze-cannon foundry.* From STRADANUS (JAN VAN DER STRAET). *Nova reperta*, Pl. III. [Antwerp, 1600?] 366

235 *Simple horizontal borer.* Cambridge University Library, MS. AD. 2883: DIEGO DE PRADO Y TOVAR. 'Encyclopaedia de Fundicion de Artilleria y su platica manuel', fols 50^v, 51^r. 1603. After photographs by courtesy of the Syndics. D. E. Woodall 367

236 *Screw-jack.* Cambridge University Library, MS. AD. 2883: DIEGO DE PRADO Y TOVAR. *Ibid.*, fol. 132^r. From photograph by courtesy of the Syndics 368

237 *Late seventeenth-century fortification.* After sketch by the author. D. E. Woodall 370

238 (Above) *Modern bastion.* After E. E. VIOLLET-LE-DUC. 'Military Architecture' (3rd ed., trans. from the French by M. MACDERMOTT), fig. 132. London, Parker, 1907. D. E Woodall. (Below) *Trace of a fortification.* After S. F. DE MEDRANO. 'L'Ingenieur pratique ou l'architecture militaire moderne', Pl. I. Brussels, 1696. D. E. Woodall 371

239 *Vauban's 'first system' of fortification.* After P. E. LAZARD. 'Vauban, 1633–1707', Pl. XVI, fig. 31. Paris, Alcan, 1934. D. E. Woodall 372

240 *The 'dispart' of a cannon.* After sketch by the author. D. E. Woodall 374

TAILPIECE. *Laying siege-guns.* After RAMELLI. 'Le diverse et artificiose machine', fig. 195. Paris, 1588. D. E. Woodall. 376

15. PRINTING *by* MICHAEL CLAPHAM

241 *Methods of printing.* After sketch by the author. T. G. Powell 379

242 *A linen-press.* After sketch by the author. T. G. Powell 382

243 *Type.* After sketch by the author. T. G. Powell 388

244 *The printer.* From HARTMAN SCHOPPER. Panoplia, *omnium illiberalium, mechanicarum aut sedentariarum artium genera continens*, etc. [Woodcuts by Jost Amman]. Sig. C. 3. Frankfurt a. M., 1568 389

245 *The typefounder.* From HARTMAN SCHOPPER. *Ibid.*, Sig. B. 8 391

246 *Composing sticks.* After sketch by the author. T. G. Powell 394

247 *A sixteenth-century printing office.* From STRADANUS (JAN VAN DER STRAET). *Nova reperta*, Pl. IV. [Antwerp, 1600?] 395

248 *A pair of cases.* From J. MOXON. 'Mechanick Exercises', Vol. 2, Pl. I. London, 1683 396

249 *Two-page forme.* After sketch by the author. T. G. Powell 397

250 *The printing press.* From *Prima Pars operũ Baptiste Mantuari*, title-page. Paris, Jodocus Badius Ascensius, 1507 398

251 *The Blaeuw or Dutch press.* From J. JOHNSON. 'Typographia or the Printers' Instructor', p. 501. London, 1824 400

252 *The improved wooden press.* From J. JOHNSON. *Ibid.*, p. 503 401

253 *A primitive rolling-press.* After sketch by the author. T. G. Powell 409

254 *The first illustration of a paper-maker at work.* From HANS SACHS. 'Eygentliche Beschreibung alle Stände . . . mit kunstreichen Figuren [by Jost Amman]', fol. F. ii. Frankfurt a. M., 1568 412

255 *Manually worked stamp-mill.* From J. BESSON. 'Theatre des instrumens', Pl. XXV. Lyons, Vincent, 1579 413

256 *The Hollander.* After D. DIDEROT and J. LE R. D'ALEMBERT (Eds). 'Encyclopédie', Planches: Vol. 5, "Papetterie", Pl. VIII. Paris, 1767. D. E. Woodall 414

257 *Mould and deckle.* From J. J. LE F. DE LALANDE. 'Descriptions des arts et métiers faites ou approvées par Messieurs de l'Académie Royale des Sciences', Vol. I, "Art de faire le papier", Pl. X. Paris, 1761 415

TAILPIECE. *French papermakers.* After J. J. LE F. DE LALANDE. *Ibid.*, Pl. XI. D. E. Woodall 416

16. BRIDGES *by* S. B. HAMILTON

258 *The Pont d'Avignon.* From drawing by R. J. Mainstone, Building Research Station, Watford, Herts. By courtesy of the artist 418

259 *Old London Bridge.* From drawing after WILLIAM KNIGHT and E. W. COOKE by R. J. Mainstone, Building Research Station, Watford, Herts. By courtesy of the artist 419

260 *Stepped coffer-dam.* Adapted from H. GAUTIER. 'Traité des ponts', Pl. XXI. Paris, 1716 420

261 *A coffer-dam.* From RAMELLI. 'Le diverse et artificiose machine', fig. III. Paris, 1588 421

262 *Pile-driver.* After B. FOREST DE BELIDOR. 'Architecture hydraulique', Vol. I, Pt II, Pl. X, fig. 2. Paris, 1750. D. E. Woodall 422

263 *Sixteenth-century pile-driver.* From B. LORINI. 'Delle Fortificationi', fig. facing p. 207. Venice, 1596 423

264 *The Rialto bridge.* From drawing by R. J. Mainstone, Building Research Station, Watford, Herts. By courtesy of the artist 424

265 *Truss-girder bridge.* From A. PALLADIO. 'I Quattro Libri dell' Architettura', Bk 3, p. 15^{r}. Venice, 1570 426

266 *The stone piers of Westminster bridge.* From J. WEALE (Ed.). 'Theory, Practice and Architecture of Bridges', Pl. XXII. London, 1843 426

267 *The timber centring.* From J. WEALE (Ed.). *Ibid.*, Pl. XXIII 427

268 *Grubenmann's bridge over the Rhine.* From E. CRESY. 'Encyclopaedia of Civil Engineering', Vol. 2, fig. 2254. London, 1847 428

269 *Grubenmann's bridge over the Limmat.* From E. CRESY. *Ibid.*, Vol. 2, fig. 2255 428

270 *The Santa Trinità bridge.* After E. CRESY. *Ibid.*, Vol. 1, fig. 184. D. E. Woodall 429

271 *Diagram showing the construction of a 'basket-handled' arch.* After sketch by the author. D. E. Woodall 430

272 *The Pont Henri IV.* From F. DE DARTEIN. 'Études sur les ponts en pierre', Vol. 1, fig. 17. Paris, Béranger, 1912 431

273 *One of Leonardo's drawings.* Diagram by the author based on Leonardo da Vinci, Codice Forster II, fol. 92^{v}. D. E. Woodall 432

274 *La Hire's force diagram.* Diagram by the author based on P. DE LA HIRE. 'Traité de méchanique', fig. on p. 456 and text. Paris, 1695. D. E. Woodall 433

275 *Diagram illustrating Danisy's study.* After diagram by the author. D. E. Woodall 434

276 *The Pont-y-Ty-Prydd.* From S. B. HAMILTON. *Trans. Newcomen Soc.*, **24**, 133, fig. 12, 1943–5. London, Newcomen Society 435

17. CANALS AND RIVER NAVIGATIONS BEFORE 1750 *by* A. W. SKEMPTON

277 *Section of a typical stanch.* From B. FOREST DE BELIDOR. 'Architecture hydraulique', Vol. 2, Pt II, Pl. XXXVIII, fig. 23. Paris, 1753 440

278 *Section of a typical 'portcullis' sluice.* After B. FOREST DE BELIDOR. *Ibid.*, Vol. 2, Pt II, Pl. XL. D. E. Woodall 441

279 *Map and longitudinal section (Stecknitz canal).* After drawing by the author based on R. WREDEN. *Beitr. gesch. Techn.*, **9**, 130, 1919. Berlin, V.D.I. Verlag. L. E. Fullbrook 443

280 *Map of canals.* After drawing by the author based on G. BRUSCHETTI. 'Istoria dei Progetti e delle Opere per la Navigazione-interna del Milanese', Pl. I. Milan, 1821. L. E. Fullbrook 445

281 *Sketch of a lock.* Florence, Biblioteca Medicea-Laurenziana, Ashb. MS. 361 (Trattato dei Pondi). After W. B. PARSONS. 'Engineers and Engineering in the Renaissance', fig. 132. Baltimore, Williams and Wilkins, 1939. D. E. Woodall 446

282 *Sketch by Leonardo da Vinci.* Milan, Biblioteca Ambrosiana, Codice Atlantico, fol. 240^{r}. From W. B. PARSONS. *Ibid.*, fig. 135 447

283 *Leonardo's sketch.* Milan, Biblioteca Ambrosiana, Codice Atlantico, fol. 341^{v}b. From W. B. PARSONS. *Ibid.*, fig. 137 448

284 *Lock at Brandenburg.* After KLEHMET. *Wschr. Arch. Ver., Berlin*, **3**, fig. 394, 1908. D. E. Woodall 449

285 *Sketch of a lock.* From H. ENGELS. *Ann. Trav. Publ. Belg.*, **1**, Pl. II, fig. 3, 1843 450

286 *Map and longitudinal section (Brussels canal).* After drawing by the author based on H. ENGELS. *Ibid.*, **1**, Pl. I, 1843. L. E. Fullbrook 451

287 *The Boesinghe lock.* After B. FOREST DE BELIDOR. 'Architecture hydraulique', Vol. 2, Pt II, Pl. XLV, Paris, 1753. D. E. Woodall 453

288 *Exeter canal.* After A. W. SKEMPTON. *Trans. Newcomen Soc.*, **29**, 1953. London, Newcomen Society. L. E. Fullbrook 456

289 *Wey canal.* After A. W. SKEMPTON. *Ibid.* L. E. Fullbrook 457

290 *View of a lock.* After R. THORESBY. '*Ducatus Leodiensius* or the Topography of Leedes', frontispiece. London, 1715. D. E. Woodall 458

291 *Map and longitudinal section (Briare canal).* After map by the author based on H. DE POMMEUSE. 'Des canaux navigables'. Paris, 1822; and P. PINSSEAU. 'Le Canal Henri IV ou Canal de Briare (1604–1943)'. Paris, Clavreuil; Orléans, Houzé, 1943. L. E. Fullbrook 461

292 *Map of the Languedoc canal.* After map by the author based on A. F. ANDREOSSY. 'Histoire du Canal du Midi', Vol. 2, Pl. I. Paris, 1804. L. E. Fullbrook 465

293 *Aqueduct over the river Cesse.* After M. DE LA ROCHE. 'Atlas et description du Canal Royal de Languedoc', Pl. V. Paris, 1787. D. E. Woodall 466

294 *Culvert under the Languedoc canal.* After B. FOREST DE BELIDOR. 'Architecture hydraulique', Vol. 2, Pt II, Pl. XLVIII, fig. 1. Paris, 1753. D. E. Woodall 467

295 *Cross-section of the St-Ferréol dam.* After drawing by the author based on A. F. ANDREOSSY. 'Histoire du Canal du Midi', Vol. 1, pp. 57–64; Vol. 2, Pl. VIII. Paris, 1804. L. E. Fullbrook 468

18. SHIPS AND SHIPBUILDING *by* G. P. B. NAISH

296 *A Mediterranean galley.* From J. FURTTENBACH. *Architetura navalis*, fig. 1. Ulm, 1629 473

297 *Broadside view of a four-masted ship.* London, British Museum, Cotton MS. Jul. E. iv. 6, fol. 25. After photograph by courtesy of the Trustees. D. E. Woodall 475

298 *Elevation and sail plan.* Cambridge, Magdalene College, Pepysian Library, MS. 2820: MATHEW BAKER. 'Fragments of Ancient English Shipwrightry', fol. 115. After photograph by courtesy of the Master and Fellows. D. E. Woodall 479

299 *Head of a scale model.* Greenwich, London, National Maritime Museum. After photograph by courtesy of the Trustees. D. E. Woodall 482

300 *Fore part of a longitudinal section.* Cambridge, Magdalene College, Pepysian Library, MS. 2934: 'Mr Dummer's Draughts of the Body of an English Man-of-War', no. 21. After photograph by courtesy of the Master and Fellows. D. E. Woodall 484

301 *Mid-ship section of a galleon.* Cambridge, Magdalene College, Pepysian Library, MS. 2820: MATHEW BAKER. 'Fragments of Ancient English Shipwrightry', fol. 19r. After photograph by courtesy of the Master and Fellows. D. E. Woodall 487

302 *Drawing-office.* Cambridge, Magdalene College, Pepysian Library, *ibid.*, fol 8v. After photograph by courtesy of the Master and Fellows. D. E. Woodall 488

303 *Sections for laying down on the floor of the mould-loft.* From W. SUTHERLAND. 'The Ship-builder's Assistant', p. 82, fig. D. London, 1711 489

304 *A fifth-rate ship.* Greenwich, London, National Maritime Museum, plan by W. KELTRIDGE. After photograph by courtesy of the Trustees. D. E. Woodall 490

305 *Manuscript draught.* Greenwich, London, National Maritime Museum, Admiralty Collection, No. 3654. After photograph by courtesy of the Trustees. D. E. Woodall 491

306 *Rigging plan.* From W. SUTHERLAND. 'The Ship-builder's Assistant', fig. A, facing p. 114. London, 1711 495

307 *Plan of sails.* From W. SUTHERLAND. *Ibid.*, fig. B, facing p. 116 496

308 *Yachts.* From W. SUTHERLAND. 'Britain's Glory: or Ship-building Unvail'd', Pt II, fig. facing p. 8. London, 1717 497

309 [*Hoys*] *during the seventeenth century.* From W. SUTHERLAND. *Ibid.*, fig. facing p. 16 498

TAILPIECE. *Forging the arm.* After D. DIDEROT and J. LE R. D'ALEMBERT (Eds). 'Encyclopédie' Planches: Vol. 7, "Marines: Forges des ancres", Pl. X. Paris, 1769. D. E. Woodall 500

19. CARTOGRAPHY, SURVEY, AND NAVIGATION TO 1400 *by* CHARLES SINGER, DEREK J. PRICE, and E. G. R. TAYLOR

310 *Eratosthenes' method.* From C. SINGER. 'A Short History of Science', fig. 27. Oxford, Clarendon Press, 1943 506

311 *The world* (*Eratosthenes*). From C. SINGER. *Ibid.*, fig. 28 507

312 *The world according to Ptolemy.* After J. O. THOMSON. 'History of Ancient Geography', fig. 60. Cambridge, University Press, 1948. D. E. Woodall 508

313 *Ptolemy's first method of projection.* After sketch by E. G. R. Taylor. D. E. Woodall 509

314 *Method of finding the centre.* After sketch by E. G. R. Taylor. D. E. Woodall 510

315 *Ptolemy's second method of projection.* After sketch by E. G. R. Taylor. D. E. Woodall 511

316 (Left) Groma; (right) *tombstone.* After R. W. SLOLEY. *Ancient Egypt*, p. 65, figs 1, 2, 1926. London, British School of Egyptian Archaeology. D. E. Woodall 512

317 *Mathematical instruments.* From C. BAILEY (Ed.). 'The Legacy of Rome', fig. 19. Oxford, Clarendon Press, 1923 512

318 *Principle of measurement.* After sketch by E. G. R. Taylor. D. E. Woodall 513

319 *Leonardo's hodometer.* Milan, Biblioteca Ambrosiana. After 'Il Codice Atlantico di Leonardo da Vinci.' Facs. edition by G. PIUMATI, fol. 1^r. Milan, Hoepli, 1894. D. E. Woodall 513

320 *A portion of the Peutinger table.* London, British Museum, Map 37.f.1. From photograph by courtesy of the Trustees 514

321 *The Kirkstead Abbey Psalter map.* Old Windsor, Beaumont College. After photograph by courtesy of the Librarian. K. F. Rowland 515

322 *Map of Isle of Thanet.* Cambridge, Trinity Hall, MS. 1. After C. HARDWICK (Ed.). '*Historia monasterii S. Augustine Cantuariensis* by Thomas of Elmham', frontispiece. London, Rolls Series, 1858. D. E. Woodall 516

323 *Three types of medieval world map.* After sketches by E. G. R. Taylor. D. E. Woodall 519

324 *The Hereford* mappa mundi. From K. MILLER. '*Mappaemundi.* Die ältesten Weltkarten', Vol. 4: 'Die Herefordkarte', fig. 1. Stuttgart, Roth'sche Verlagshandlung, 1896 520

325 *The* Carte Pisane. From E. F. JOMARD. 'Les monuments de la géographie', Pls L–LI. Paris, [1854] 523

326 (Left) *Scheme of rhumb-lines*; (right) *the Italian division of the compass.* After sketches by E. G. R. Taylor. D. E. Woodall 524

327 *The 'Catalan Atlas'.* From VICOMTE DE SANTAREM. 'Atlas des Cartes', Pl. XXXII. Paris, 1841 525

328 *One method of using the cross-staff.* From W. RYFF. 'Der furnembsten notwendigsten der ganzen Architectur angehörigen Mathematischen und Mechanischen Künst', Sig. I. 3^v. Nuremberg, Johann Petreius, 1547 527

329 *Shadow-scales.* After sketches by E. G. R. Taylor. D. E. Woodall 528

TAILPIECE. *Measuring heights.* After C. BARTOLI. 'Del modo di misurare', p. 32^v. Venice, 1589. D. E. Woodall 529

20. CARTOGRAPHY, SURVEY, AND NAVIGATION, 1400–1750, *by* E. G. R. TAYLOR

330 *Outline of Claudius Clavus's map.* After E. J. P. BURON (Ed. and Trans.). 'Ymago mundi de Pierre d'Ailly', Vol. 3, Pl. XXX. Paris, Librairie Orientale et Américaine Maisonneuves Frères, 1930. D. E. Woodall 532

331 *Outline of the lower portion of Etzlaub's road-map.* London, British Museum, Map C.2.a. After photograph by courtesy of the Trustees. D. E. Woodall 534

332 *Globular projection.* After sketch by the author. D. E. Woodall 536

333 *Method of measuring distance.* After sketch by the author. D. E. Woodall 537

334 *Waldseemüller's* polimetrum. From [GREGOR REISCH]. *Margarita Philosophica*, Appendix. Strasbourg, Johannes Gruninger, 1512 538

335 *Two surveying-instruments.* From 'Questi et inventioni diverse de Nicolo Tartalea Brisciano', pp. 56, 65. Venice, Ruffinello, 1546 539

336 *Leonard Digges's 'theodelitus'.* From L. DIGGES and T. DIGGES. 'A Geometrical Treatise named *Pantometria*', Sig. H. iii^v. London, 1571 541

337 *The use of Digges's 'Topographical Instrument'.* From L. DIGGES and T. DIGGES. *Idem.*, Sig. K. i 542

338 *Surveyors at work.* From A. RATHBONE. 'The Surveyor', vignettes from title-page. London, 1616 543

339 *'Regiment of the North Star'.* After sketch by the author. D. E. Woodall 545

340 *The 'Jacob's staff'.* From E. STONE. 'Construction and Principal Uses of Mathematical Instruments', Pl. XX, fig. 12. London, 1758 546

341 *The back-staff.* From E. STONE. *Ibid.*, Pl. XX, figs 8, 11 551

342 *The principle of Hadley's octant.* After sketch by A. R. Hall. D. E. Woodall 555

22. PRECISION INSTRUMENTS TO 1500 *by* DEREK J. PRICE

343 *Astronomical measuring instruments.* After reconstructions by the author based on PTOLEMY. 'Almagest'. E. Norman 589

344 *The* triquetrum. After reconstruction by the author based on PTOLEMY. *Ibid.* E. Norman 590

345 *The four-cubit dioptra.* After reconstruction by the author based on PTOLEMY. 'Almagest', E. Norman 591

346 *The armillary* astrolabon. After reconstruction by the author based on PTOLEMY. *Ibid.* E. Norman 592

347 *The torquetum.* After H. MICHEL. *Ciel et Terre*, **60**, nos 11–12, 197, fig. 1, 1944. Brussels, Société Belge d'Astronomie, de Météorologie et de Physique du Globe. E. Norman 593

348 *The* rectangulus. After H. MICHEL. *Ibid.*, **60**, nos 11–12, 201, fig. 3, 1944. Brussels, Société Belge d'Astronomie, de Météorologie et de Physique du Globe. E. Norman 594

349 (A) *Gerbert's sighting-tube.* St Gallen, Stifts-Bibliothek, MS. 18. After H. MICHEL. *Ibid.*, **70**, 176, fig. 1, 1954. Brussels, Société Belge d'Astronomie, de Météorologie et de Physique du Globe. E. Norman. (B) *Similar tube.* Munich, Staatsbibliothek, MS. 17405. After H. MICHEL. *Ibid.*, **70**, 180, fig. 7, 1954. Brussels, Société Belge d'Astronomie, de Météorologie et de Physique du Globe. E. Norman 595

350 Skaphe, *or hemicycle sun-dial.* London, British Museum. Reconstruction from F. A. B. WARD. 'Handbook of the Collections Illustrating Time Measurement', Pt I, Pl. II. London, Science Museum Handbook, 1947. E. Norman 596

351 *Sundials.* (A) *Egyptian wedge-dial.* After P. CASANOVA. *Syria*, **4**, Pl. XLV, 1923. Paris, Institut Français d'Archéologie de Beyrouth. (B) *Roman 'ham' dial.* After D. COMPARETTI and G. DE PETRA. 'La Villa Ercolanese dei Pisoni', Pl. XVII, no. 4. Turin, 1883. (C) *Saxon dial.* After photograph of painting by NOWELL EDWARDS, by courtesy of the Dean and Chapter of Canterbury Cathedral. (D) *Islamic dial.* After D. COMPARETTI and G. DE PETRA. *Syria*, **4**, Pl. XLVII, no. 7, 1923. Paris, Institut Français d'Archéologie de Beyrouth. (E) *'Chilindre'.* Cambridge, Whipple Museum of the History of Science. After photograph by permission of the University of Cambridge. (F) *Ring-dial.* Munich, Deutsches Museum. After photograph by courtesy of the Director. (G) *Navicula.* Oxford, Museum of the History of Science. After R. T. GUNTHER. 'Early Science in Oxford', Vol. 2, p. 41. Oxford, Oxford Historical Society for Publications, 1932. (H) *Universal rectilinear dial.* Cambridge, Whipple Museum of the History of Science. After photograph by permission of the University of Cambridge. (I) *Horary quadrant.* London, British Museum, Department of British and Medieval Antiquities. After photograph by courtesy of the Trustees. (A–I) E. Norman 597

352 *Roman equatorial dial.* Oxford, Museum of the History of Science. After R. T. GUNTHER. 'Early Science in Oxford', Vol. 2, p. 17. Oxford, Oxford Historical Society for Publications, 1932. E. Norman 598

353 *Syrian double-dial.* After S. REICH and G. WEIT. *Bull. Inst. franç. archéol. orientale*, **38**, 195, fig. 1, 1939. Paris, Institut Français d'Archéologie Orientale. E. Norman 599

354 *An early German horizontal dial.* London, British Museum. After photograph by courtesy of the Trustees. E. Norman 600

355 (A) *Constant-head clepsydra*; (B) *parastatic water-clock.* After sketch by the author, based on A. G. DRACHMANN. *Acta hist. sci. nat. med., Kbh.*, **4**, 18, 20, 1948. Copenhagen, Munksgaard. E. Norman 602

356 *Zodiac-regulated water-clock.* After sketch by the author based on A. G. DRACHMANN. *Ibid.*, 28 ff. Copenhagen, Munksgaard. E. Norman 603

357 *Principle of the stereographic projection.* After sketch by the author. E. Norman 604

358 (Left) *Rotating star-map*; (right) mater, *plate, and star-map.* After sketch by the author. E. Norman 605

359 *The component parts of an astrolabe.* After sketch by the author based on S. G. FRANCO. 'Catálogo Crítico de Astrolabios Existentes en España', fig. 7. Madrid, Instituto Histórico de Marina, 1945. E. Norman 607

360 *Hero's dioptra (reconstructed diagram).* After sketch by A. G. Drachmann. E. Norman 610

361 *Hero's dioptra.* After sketch by A. G. Drachmann. E. Norman 611

362 *Fifteenth-century armillary sphere.* Cambridge, Whipple Museum of the History of Science. After photograph by permission of the University of Cambridge. E. Norman 613

363 *Nocturnal.* Dresden, Mathematisch-Physikalisch Salon. After photograph by courtesy of the Landesfotothek, Dresden. E. Norman 615

364 *Reconstruction of the fragments of an instrument.* After J. THEOPHANIDIS. *Praktika tes Akademias Athenon*, **9**, 140, fig. C, 1934. Academy of Athens. E. Norman 617

TAILPIECE. *A medieval astronomer.* London, British Museum, Cotton MS. Claud. E. IV, Pt II, fol. 201. After R. T. GUNTHER. 'Early Science in Oxford', Pt II: 'Mathematics', frontispiece. London, Oxford University Press, 1922. D. E. Woodall 619

23. THE MANUFACTURE OF SCIENTIFIC INSTRUMENTS FROM *c* 1500 TO *c* 1700
by DEREK J. PRICE

365 *Trade-card of Henry Sutton.* From G. H. GABB. *Archaeologia*, **86**, 102, fig. 1, 1937. London, Society of Antiquaries of London 623

366 *Bramer's* Trigonometria. From E. R. KIELY. 'Surveying Instruments', fig. 143. New York, Columbia University, 1947 626

367 *Galileo's 'geometrical and military compass'.* After [A. FAVARO *et al.*, Eds]. 'Opere di Galileo Galilei. Edizione Nazionale', Vol. 2, Pl. facing p. 342. Florence, 1891. D. E. Woodall 628

368 *Diagrammatic views of a Leeuwenhoek microscope.* After C. DOBELL. Antony van Leeuwenhoek and his "Little Animals"', Pl. XXXI. London, Bale and Danielsson, 1932. D. E. Woodall 631

369 *Newton's original drawing of his reflecting telescope.* London, Royal Society, MS. Letters, N(1), No. 37. From photograph by courtesy of the Officers 632

370 *John Marshall's microscope.* After J. HARRIS, *Lexicon technicum*, London, 1704. D. E. Woodall 633

371 *John Yarwell's trade-card.* Cambridge, Whipple Museum of the History of Science. After photograph by permission of the University of Cambridge. D. E. Woodall 634

372 *Microscope made for Robert Hooke.* After photograph by courtesy of the Director of the Science Museum, South Kensington, London. D. E. Woodall 635

373 *Thermometers.* From ACCADÈMIA DEL CIMENTO. 'Saggi di Naturali Esperienze fatte nell' Accademia del Cimento', Pl. I. Florence, 1841 637

374 *Electrical machine.* From F. HAUKSBEE. 'Physico-Mechanical Experiments on Various Subjects', Pl. VII. London, 1709 638

375 *View of part of an observatory.* From JOHN HEVELIUS. *Machina coelestis*, p. 243, fig. N. Danzig, 1673 639

376 *Dudley's quadrant.* From R. DUDLEY. 'Arcano dell Mare', Vol. 3, Pt I, fig. 44. Florence, 1647 640

377 *Five-foot mural quadrant.* From J. J. LE F. DE LALANDE 'Astronomie', Vol. 2, Pl. XVI, fig. 155. Paris, 1764 641

378 *Ramsden's circular dividing-engine.* From J. RAMSDEN. 'Description of an Engine for dividing Mathematical Instruments', Pl. I. London, 1777 643

379 *Workshop.* From D. DIDEROT and J. LE R. D'ALEMBERT (Eds). 'Encyclopédie', Planches: Vol. 5, "Instruments de mathématiques", Pl. I. Paris, 1767 644

380 *Atwood's machine.* After G. ADAMS. 'Lectures on Natural and Experimental Philosophy' (2nd ed.), Vol. 5, Pl. I to Vol. 3, fig. 13. London, 1799. D. E. Woodall 645

381 *Apparatus for making experiments.* From [ABBÉ NOLLET]. 'Lectures in Experimental Philosophy . . . translated from the French by John Colson', Pl. XVIII, fig. 17. London, 1752 646

24. MECHANICAL TIMEKEEPERS *by* H. ALAN LLOYD

382 *Alfonso X's mercury clock.* Based on ALFONSO OF CASTILE. 'Libros del Saber de Astronomia del Rey Don Alfonso X de Castille' (ed. by M. RICO Y SINOBAS), Vol. 4, pp. 65–76. Madrid, 1866. F. Janca 649

383 *Villard de Honnecourt's rope-escapement.* Paris, Bibliothèque Nationale, MS. franç. 19093, fol. 23. From R. WILLIS (Trans. and Ed.). 'Facsimile of the Sketch-Book of Willars de Honecort', Pl. XLIII. London, 1859 649

384 *A fifteenth-century mechanical clock.* Basel, Collection of Dr Eugen Geschwind. After H. ALAN LLOYD. 'The English Domestic Clock', fig. 6. London, privately printed, 1938. F. Janca 650

385 *Early form of simple striking-train.* After the original in the collection of Mr H. Alan Lloyd. F. Janca 651

386 *Early monastic alarm clock.* Nuremberg, Germanisches Museum. Based on photograph by courtesy of the Director. F. Janca 652

387 *Dondi's incomplete sketch of his going-train.* Oxford, Bodleian Library, MS. Laud. Mics. 620, fol. 10^{v}. Based on photograph by courtesy of the Curators. F. Janca 653

388 *Dondi's lunar train.* Oxford, Bodleian Library, *ibid.*, fol. 74^{r}. Based on photograph by courtesy of the Curators. F. Janca 654

389 *The mechanical cock.* After photograph by courtesy of Mr R. P. Howgrave-Graham. F. Janca 655

390 *Diagram (head).* After A. UNGERER and T. UNGERER. 'L'Horloge astronomique de la Cathédrale de Strasbourg', p. 7. Strasbourg, Imprimerie Alsacienne, 1922. L. E. Fullbrook 655

391 *Diagram (wings).* After A. UNGERER and T. UNGERER. *Ibid.*, p. 11. L. E. Fullbrook 655

392 *Reconstruction of a clock.* After photograph by courtesy of Professor E. Zinner. F. Janca 656

393 *Leonardo's drawing of a fusee.* Milan, Biblioteca Ambrosiana. From 'Il Codice Atlantico di Leonardo da Vinci', facs. edition by G. PIUMATI, fol. 377ᵛb. Milan, Hoepli, 1894 657

394 *The stackfreed.* Drawing by F. Janca 657

395 *Hog's-bristle regulation.* Kassel, Hessisches Landesmuseum. After photograph by courtesy of the Director. F. Janca 658

396 *A little clock.* Nuremberg, Germanisches Museum. Based on photograph by courtesy of the Director. F. Janca 659

397 *Baldewin's clock.* Kassel, Hessisches Landesmuseum. After photograph by courtesy of the Director. F. Janca 659

398 *Part of the train.* Kassel, Hessisches Landesmuseum. After photograph by courtesy of the Director. F. Janca 660

399 *Burgi's remontoire.* Kassel, Hessisches Landesmuseum. After photograph by courtesy of the Director. F. Janca 661

400 *Burgi's cross-beat escapement.* After H. VON BERTELE. *Horological J.*, **95**, 814, fig. 31, 1953. London, British Horological Institute. F. Janca 662

401 *Galileo's pendulum escapement.* After photograph of model in the Science Museum, South Kensington, London. By courtesy of the Director. D. E. Woodall 663

402 *Huygens's first pendulum clock.* CHRISTIAAN HUYGENS. *Horologium.* The Hague, 1658. From SOCIÉTÉ HOLLANDAISE DES SCIENCES. 'Œuvres complètes de Christiaan Huygens', Vol. 17, p. 43, fig. 8. The Hague, Nijhoff, 1932 664

403 *Huygens's clock.* From CHRISTIAAN HUYGENS. *Horologium oscillatorium*, figs 1–3, facing p. 5. Paris, 1673 664

404 (Left) *William Clement's anchor-escapement*; (right) *Graham's dead-beat escapement.* Drawings by F. Janca 665

405 *Diagram.* Drawing by H. Alan Lloyd 666

406 *Huygens's balance-spring.* From "The watch of M. Hugens." *Phil. Trans.* **10**, no. 112, Tab. 1, fig. 4, 1675 666

407 *Equation movement.* After photograph by courtesy of Mr H. Alan Lloyd. F. Janca 666

408 *Early forms of balance-spring.* (A) Kassel, Hessiches Landesmuseum. After photograph of watch made by Christof Lehman, Copenhagen, *c* 1675, by courtesy of the Director; (B) after photograph of watch made by S. Watson, *c* 1685, by courtesy of Mr H. Alan Lloyd. F. Janca 667

409 *Edward Barlow's rack-and-snail strike.* F. Janca 668

410 *Early repeating-work by Daniel Quare.* F. Janca 669

411 *The Harrisons' grasshopper-escapement.* London, Guildhall, Clockmakers' Library, MS. 6026/1. After photograph by courtesy of the Librarian. F. Janca 670

412 *Graham's cylinder-escapement.* After T. P. CAMERER-CUSS. 'The Story of Watches', p. 105, diagram III. London, McGibbon and Kee, 1952. F. Janca 671

413 *Amant's pin-wheel escapement.* Drawing by F. Janca 672

414 *Mudge's lever-escapement.* After T. P. CAMERER-CUSS. 'The Story of Watches', p. 117, diagram IV. London, McGibbon and Kee, 1952. F. Janca 673

TAILPIECE. *The earliest printed representation.* From *Ars memorativa*, facsimile edition by Dr Bennofilser, no. 28. Augsburg, Himmer, 1925 675

25. INVENTION IN CHEMICAL INDUSTRIES *by* F. W. GIBBS

415 *Drebbel's automatic furnace.* Cambridge, University Library, MS. Ll.5.8, fols 217^{v}–218^{r}. From photograph by courtesy of the Syndics 680

416 *Charcoal-burning.* After 'Descriptions des arts et métiers faites ou approvées par Messieurs de l'Académie Royale des Sciences', Vol. I: "Art du Charbonnier" by H. L. DUHAMEL-DUMONCEAU, sole plate. Paris, 1717. D. E. Woodall 684

417 *Glauber's beehive furnace.* From J. R. GLAUBER. 'The Works of . . . Glauber' (Eng. trans. by C. PACKE), Pt I, fig. facing p. 188. London, 1689 686

418 *Desaguliers's scheme for heating boilers.* London, Royal Society. 'Classified Papers', Vol. 8, No. 40. After photograph by courtesy of the Officers. D. E. Woodall 687

419 *Plant for manufacturing 'oil of petre'.* From M. EELE. *Phil. Trans.*, **19**, fig. facing p. 529, 1697 688

420 *Manufacture of tinplate* (I). From D. DIDEROT and J. LE R. D'ALEMBERT (Eds). 'Encyclopédie', Planches: Vol. VI, "Métallurgie", Pl. I. Paris, 1768 690

421 *Manufacture of tinplate* (II). From D. DIDEROT and J. LE R. D'ALEMBERT (Eds). *Ibid.*, Pl. II 691

422 *Tropical indigo manufactory.* From P. POMET. 'Histoire générale des drogues', p. 152. Paris, 1694 693

423 *The German glass-furnace.* From BARON DE HOLBACH (Trans.). 'Art de la verrerie de Neri, Merret et Kunckel', Pl. III. Paris, 1752 699

424 *The Amsterdam glass-furnace.* From BARON DE HOLBACH (Trans.). *Ibid.*, Pl. IV 700

425 *The manufacture of potash.* From BARON DE HOLBACH (Trans.). *Ibid.*, Pl. XIII 701

426 *General view of a soap-works.* After 'Descriptions des arts et métiers faites ou approvées par Messieurs de l'Académie Royale des Sciences', Vol. 8, "L'art du savonnier", Pl. IV. Paris, 1774. D. E. Woodall 704

PLATES

1 *Portrait by Tommaso da Modena.* Treviso Seminario. Copyright photograph Alinari, Florence

2A *'Gin Lane'.* London, British Museum, Print Room, No. W/P. 64. Photograph by courtesy of the Trustees

2B *The Buxheim St Christopher.* Manchester, John Rylands Library. Copyright photograph

3 *'The Iron Mountain'.* Reproduced by courtesy of Mr John Sealy. Exhibited in Slatter Gallery's 1955 Exhibition of Dutch and Flemish Masters, London, W. I.

4A *Post-mill at Parham.* Photograph by courtesy of Mr Rex Wailes

4B *The same mill, showing the brake-wheel.* Photograph by courtesy of Mr Rex Wailes

5A *Interior of the substructure of the post-mill at Parham.* Photograph by courtesy of Mr Rex Wailes

5B *The same mill, showing the drive.* Photograph by courtesy of Mr Rex Wailes

6 *The wheelwright's workshop.* Line engraving by Stanley Anderson, C.B.E.

7 *The cooper's workshop.* Line engraving by Stanley Anderson, C.B.E.

8A *Vaucanson's loom.* Paris, Conservatoire National des Arts et Métiers. Copyright photograph

8B *Detail of* sprang *fabric.* Reproduced from frame 5 of the filmstrip 'The Story of Knitting'. London, International Wool Secretariat

9A *Spanish knitted altar-glove.* London, Victoria and Albert Museum. Photograph Crown copyright reserved

9B *Florentine coat.* London, Victoria and Albert Museum. Photograph Crown copyright reserved

9C *Charles I's vest.* London, Victoria and Albert Museum. Photograph Crown copyright reserved

10A *Shroud of St-Josse.* Paris, Louvre, Islamic Room. Copyright photograph Archives Photographiques, Paris

10B *Head of a gryphon.* London, Victoria and Albert Museum, No. 64–1893. Photograph Crown copyright reserved

10C *Design in weft-faced figured tabby weave.* London, Victoria and Albert Museum, No. 243–1890. Photograph Crown copyright reserved

11A *Silk with lion pattern.* From O. FALKE. 'Kunstgeschichte der Seidenweberei', Vol. 2, fig. 239. Berlin, Wasmuth, 1913

11B *'Elephant' silk.* Berlin, Kunstgewerbemuseum. Copyright photograph Kunstgewerbemuseum, Berlin

12A *The 'Maenad' silk.* Sens, Cathedral Treasury. Copyright photograph Archives Photographiques, Paris

12B *Fragment of one of the robes.* London, British Museum, Department of British and Medieval Antiquities. Photograph by courtesy of the Trustees

12C *German weft-faced figured twill silk.* London, Victoria and Albert Museum. Photograph Crown copyright reserved

13A *Spanish tabby tissue.* London, Victoria and Albert Museum, No. 275–1894. Photograph Crown copyright reserved

13B *North Italian silk twill-ground tissue.* London, Victoria and Albert Museum, No. 832–1894. Photograph Crown copyright reserved

13C *Italian silk tabby tissue.* London, Victoria and Albert Museum, No. 1274–1864. Photograph Crown copyright reserved

13D *Italian silk tabby tissue.* London, Victoria and Albert Museum, No. T. 66–1910. Photograph Crown copyright reserved

14A *North Italian silk twill-ground tissue.* London, Victoria and Albert Museum, No. 1304–1864. Photograph Crown copyright reserved

14B *Hispano-Moresque silk satin-ground tissue.* London, Victoria and Albert Museum, No. 830–1894. Photograph Crown copyright reserved

14C *Hispano-Moresque silk satin-ground tissue.* London, Victoria and Albert Museum, No. 678a–1896. Photograph Crown copyright reserved

14D *Italian silk brocatelle.* London, Victoria and Albert Museum, No. 146–1891. Photograph Crown copyright reserved

15A *Four-heald twill damask silk.* Maastricht, Treasury of the Church of St Servatius. Copyright photograph Giraudon, Paris

15B *Italian brocaded damask.* London, Victoria and Albert Museum. Photograph Crown copyright reserved

15C *Italian figured velvet.* London, Victoria and Albert Museum, No. 18–1892. Photograph Crown copyright reserved

16 *Manuscript miniature.* London, British Museum, Add. MS. 24189, fol. 16. Photograph by courtesy of the Trustees

17 (Above) *matchlock gun.* (Below) *wheel-lock rifle.* Cambridge, Fitzwilliam Museum. Photographs reproduced by permission of the Syndics

18 *Chinese barge.* From SIR GEORGE L. STAUNTON. 'An Authentic Account of an Embassy to China', Pl. xxxv. London, 1797

19 *Leonardo da Vinci's plan.* Royal Library, Windsor. By gracious permission of H.M. The Queen

20 *Sectional diagram.* From photograph by courtesy of the Director of the Science Museum, South Kensington, London

21A *The* Henry Grâce à Dieu. Cambridge, Magdalene College, MS. 229, the Anthony Anthony Roll. Photograph by courtesy of the Master and Fellows

21B *The* Grand Mistress. London, British Museum, Add. MS. 22047. Photograph by courtesy of the Trustees

22 *The arrival of the Elector Palatine.* Haarlem, Frans Halsmuseum. Copyright photograph

23 *The* Sovereign of the Seas. London, British Museum, Print Room. Photograph by courtesy of the Trustees

24A *Contemporary scale model.* Greenwich, London, National Maritime Museum. Photograph by courtesy of the Trustees

24B *Contemporary rigged scale model.* Greenwich, London, National Maritime Museum. Photograph by courtesy of the Trustees

25 *Gunner's level.* Dresden, Mathematisch-Physikalisch Salon. Photograph by courtesy of the Landesfotothek, Dresden

26A *The octagonal 'Tower of the Winds'*. From J. STUART and N. REVETT. 'Antiquities of Attica', Vol. I, Pl. III. London, 1762

26B *Elias Allen*. From D. J. PRICE. *Endeavour*, 14, 93, fig. 4, 1955. Reproduced by courtesy of the Editor and of the Director of the Science Museum, South Kensington, London.

27A *George Adams's compressing and exhausting air-pump*. London, Science Museum. Photograph by courtesy of the Director

27B *Orrery*. Oxford, Museum of the History of Science. Photograph by courtesy of the Curator

28 *Alchemical laboratory*. Florence, Palazzo Vecchio. Copyright photograph Alinari, Florence

29 *Jeweller's workshop*. Florence, Palazzo Vecchio. Copyright photograph Alinari, Florence

30 *Painting by G. M. Butteri*. Photograph Gabinetto Fotografico della Soprintendenza alle Gallerie di Firenze

31 *Dyers at work*. Florence, Palazzo Vecchio. Copyright photograph Alinari, Florence

32A *An early turret-clock*. London, Science Museum. Photograph by courtesy of the Director

32B *An early spring-driven clock*. Antwerp, Koninklijk Museum voor Schone Kunsten. Copyright photograph Pfelt, Antwerp

ABBREVIATIONS OF PERIODICAL TITLES

(AS SUGGESTED BY THE WORLD LIST OF SCIENTIFIC PERIODICALS)

Abh. Ges. Wiss. Göttingen	Abhandlungen der Königlichen Gesellschaft der Wissenschaften zu Göttingen, mathematisch-physikalische Klasse. Göttingen
Acta hist. sci. nat. med., Kbh.	Acta historica Scientiarum naturalium et medicinalium. Copenhagen
Amer. hist. Rev.	American Historical Review. American Historical Association. New York
Ann. Ponts Chauss.	Annales des Ponts et Chaussées. Ministère des Travaux publics et des Transports. Paris
Ann. Sci.	Annals of Science. A Quarterly Review of the History of Science since the Renaissance. London
Ann. Trav. publ. Belg.	Annales des Travaux publics de Belgique. Brussels
Antiquity	Antiquity. A Quarterly Review of Archaeology. Newbury, Berks.
Archaeol. Cambrensis	*Archaeologia Cambrensis.* Cambrian Archaeological Association. London
Archaeol. J.	The Archaeological Journal. Royal Archaeological Institute of Great Britain and Ireland. London
Archaeologia	*Archaeologia* or Miscellaneous Tracts relating to Antiquity. Society of Antiquaries. London
Beitr. Gesch. Tech. Industr.	Beiträge zur Geschichte der Technik und Industrie. Jahrbuch des Vereins Deutscher Ingenieure. (Continued as *Technikgeschichte.*) Berlin
Blackwood's Mag.	Blackwood's Magazine. Edinburgh
Bull. Inst. franç. Archéol. orientale	Bulletin de l'Institut Français d'Archéologie Orientale. Cairo
Bull. Soc. R. Archaeol., Bruxelles	Bulletin de la Société royale d'Archéologie de Bruxelles. Brussels
Burlington Mag.	Burlington Magazine. London
Centaurus	Centaurus; International Magazine of the History of Science and Medicine. Copenhagen
Ciel et Terre	Ciel et Terre. Société Belge d'Astronomie, de Météorologie et de Physique du Globe. Brussels
Clessidra	La Clessidra Associazione degl' Orologiai d'Italia. Rome
Connoisseur	The Connoisseur. London
Dolphin	The Dolphin. Limited Editions Club. New York

Econ. Hist. Rev.	Economic History Review. Economic History Society. Cambridge
Endeavour	Endeavour. A Quarterly Review designed to record the Progress of the Sciences in the Service of Mankind. London
Gaz. Beaux-Arts.	Gazette des Beaux-Arts. Paris
Glastekn. Tidskr.	Glasteknisk Tidskrift. Glasinstitutet i Växjö. Växjö
Hist. Acad. R. Sci.	Histoire de l'Académie royale des Sciences avec les Mémoires de Mathématique et Physique. Paris
Horol. J., Lond.	Horological Journal. British Horological Institute. London
Isis	Isis. History of Science Society. Cambridge, Mass.
J. Brit. astr. Ass.	Journal of the British Astronomical Association. London
J. Cork hist. archaeol. Soc.	Journal of the Cork Historical and Archaeological Society. Cork
J. Hist. Med.	Journal of the History of Medicine and Allied Sciences. New York
J. Instn civ. Engrs	Journal of the Institution of Civil Engineers. London
J. Jr Instn Engrs	Journal and Record of Transactions of the Junior Institution of Engineers. London
J. polit. Econ.	Journal of Political Economy. Chicago
J. Soc. Arts	Journal of the Society [afterwards Royal Society] of Arts. London
Jb. kunsthist. Samml.	Jahrbuch der kunsthistorischen Sammlungen des allerhöchsten Kaiserhauses. Vienna
Mariner's Mirror	Mariner's Mirror. Journal of the Society for Nautical Research. London
Meded. Rijksmus. Gesch. Natuurwet.	Mededeeling uit het Rijksmuseum voor de Geschiedenis der Natuurwetenschappen. [Communications from the National Museum of the History of Science]. Leiden
Min. Proc. Instn civ. Engrs	Minutes of Proceedings of the Institution of Civil Engineers. London
Numism. Chron.	The Numismatic Chronicle and Journal of the Royal Numismatic Society. London
Observatory	Observatory. London
Occ. Publ. Soc. naut. Res.	Occasional Publications of the Society for Nautical Research. London
Phil. Trans.	Philosophical Transactions of the Royal Society. London
Prakt. Akad. Athen.	Praktika tes Akademias Athenon. Athens
Quart. J. Econ.	Quarterly Journal of Economics. Cambridge, Mass.
Relaz. Congr. int. Sci. ist.	Relazione del Congresso internazionale di Scienze istoriche. [International Congress of historical Sciences]. Rome

Rev. belge Philol. Hist.	Revue belge de Philologie et d'Histoire. Société pour le Progrès des Études philologiques et historiques. Brussels
Saml. Svenska Fornskriftsällskap.	Samlingar af Svenska Fornskriftsällskapet. Stockholm
Schweiz. Bauztg	Schweizerische Bauzeitung. Wochenschrift für Architektur, Ingenieurwesen, Maschinentechnik. Zürich
Sprechsaal	Sprechsaal für Keramik, Glas, Email. Fach- und Wirtschaftsblatt für die Silikatindustrien. Coburg
Stahl u. Eisen, Düsseldorf	Stahl und Eisen. Zeitschrift für das Deutsche Eisenhüttenwesen. Verein Deutscher Eisenhüttenleute. Düsseldorf
Syria	Syria. Revue d'Art oriental et d'Archéologie. Institut Français d'Archéologie de Beyrouth. Paris
Tech. Stud. fine Arts	Technical Studies in the Field of the Fine Arts. Fogg Art Museum, Harvard University. Cambridge, Mass.
Town Plann. Rev.	Town Planning Review. Liverpool
Trans. Newcomen Soc.	Transactions. Newcomen Society for the Study of the History of Engineering and Technology. London
V.D.I. Jb.	Verein Deutscher Ingenieure. Jahrbuch. Berlin
Wasserwirtschaft	Die Wasserwirtschaft. Stuttgart
Woodworker, Lond.	The Woodworker. London
Wschr. Arch. Ver. Berlin	Wochenschrift des Architekten-Vereins zu Berlin. Berlin
Z. Ver. dtsch. Ing.	Zeitschrift des Vereins Deutscher Ingenieure. Berlin
Z. Ver. dtsch. Zuckerind.	Zeitschrift des Vereins der Deutschen Zuckerindustrie. Berlin
Z. Ver. lübeckische Gesch.	Zeitschrift des Vereins für Lübeckische Geschichte und Altertumskunde. Lübeck

I

FOOD AND DRINK

R. J. FORBES

I. NEW FOOD FROM A NEW WORLD

THE period now to be considered is marked by a great change in diet, as the combined result of several factors. Such were the acquisition of new foodstuffs; changing agricultural techniques; improvements in milling techniques; progress in testing, preparing, and preserving food; and changing views on diet and the rise of dietetics as a science.

Direct overseas contact with the Indies and the Far East, and the discovery of the New World, confronted Europe with a wide new range of animals and plants. During the sixteenth and seventeenth centuries many new food-crops were adopted by the European farmer. Apart from such important new drugs as ipecacuanha, guaiacum, and quinine, and the narcotics coca-leaf, Indian hemp, and opium [1], four new plant crops—potato, maize, rice, and oil-seed—began to play their part in the agriculture and diet of Europe. Sugar-cane also was soon cultivated in colonial plantations in the tropics and even in parts of Europe, as was tobacco. Sugar acquired added importance when the new beverages tea, coffee, and cocoa were introduced. The only new contribution to the table from the animal world, however, was the turkey, which was introduced from Mexico about 1520 and became common Christmas fare a century later.

The *potato* was the most important addition to European farming, though its introduction took the full span of three centuries [2]. Its cultivation in the Andes region of western South America began at least 2000 years before the Spanish conquest, by which time it dominated the life of inhabitants of the highlands of Peru and Bolivia. They not only ate it freshly cooked, but preserved it as a durable food resisting damp and frost.

The potato was long thought to have reached Europe from Virginia, whereas in fact it was introduced there from Europe late in the seventeenth century. Spain was the first European country in which the potato was grown and eaten, certainly not later than 1570. Probably an independent introduction into England, and thence to Ireland, occurred some years later. In both cases tubers of the species *Solanum andigenum*, native in the northern Andean region, were imported. The plant is first illustrated in Gerard's 'Herball' (1597) (figure 1).

Early confusion between the potato (*S. tuberosum*, *S. andigenum*), the sweet potato (*Ipomoea batatas*—known in Europe since the fifteenth century), the yams (*Dioscorea*), the Jerusalem artichoke (*Helianthus tuberosus* L), and other plants yielded the strangely varied names for it in the European languages (potato, *patata*, *pomme de terre*, *Kartoffel*). The native name seems to have been 'papa'.

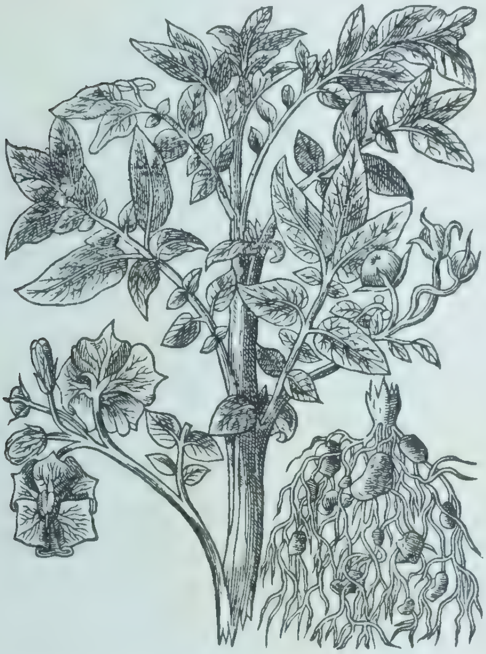

FIGURE 1—*The potato plant. From Gerard's* Herball, *1597. He wrote: 'The roote is thicke, fat and tuberous; not much differing either in shape, colour or taste from the common [i.e. sweet] Potatoes.' Gerard was responsible for the mistaken belief that potatoes came to Britain from Virginia.*

By the end of the sixteenth century the potato was common in Spain and Italy, whence it travelled to France and through Burgundy to Germany. As it was used by the Spanish navy it may have come to Ireland from the stores of the wrecked Armada ships; the story that Ralegh introduced it is unlikely to be true. It was preceded in England by the sweet potato (figure 2); hence when the true potato went from Ireland to the new colony of Virginia it was called the Irish potato.

In 1616 the potato was still a luxury of the royal table in France. Both there and in Germany it was praised by botanists and poets, and the desirability of cultivating it in less fertile areas was propagated even in sermons. By 1712 it had reached the Bohemian border, but here as elsewhere it proved unpopular with farmers. In 1764 a Prussian edict ordered its cultivation in certain backward areas. The peasants remained recalcitrant, regarding the potato as fit only for the poorest folk, and as liable to cause disease. The cultivation of the potato in eastern Europe owed much to the encouragement of Frederick the Great of Prussia (reigned 1740–86), and, from about 1785, to its use as an industrial source of starch. The manufacture of alcohol by fermenting mixtures of wheat and potato was also begun. This was soon displaced by the distillation of alcohol from fermented potato-mashes alone. Fully developed cultivation of potatoes in central Europe, however, began only in the nineteenth century.

In Ireland, owing to the great indigence of the peasantry, the potato became established in the late sixteenth century. In the next century it dominated Irish agriculture, with the result that Ireland suffered the full disadvantage of a single-crop economy. In the eighteenth century the food of the Irish, consisting mainly of milk and potatoes, became a byword for extreme poverty. The disastrous Irish potato blight of 1845–6 proved the delicacy of the balance between famine and subsistence. In other countries development lay between the extreme examples of Ireland and Germany. In the Lowlands of Scotland the introduction of the potato led to greatly improved methods of husbandry and offered an important source of food to an increasingly industrialized area. In the Highlands it little affected agriculure, and even retarded cultural development. In the rest of Britain, as in France, the potato was not a common article of diet before the late eighteenth century.

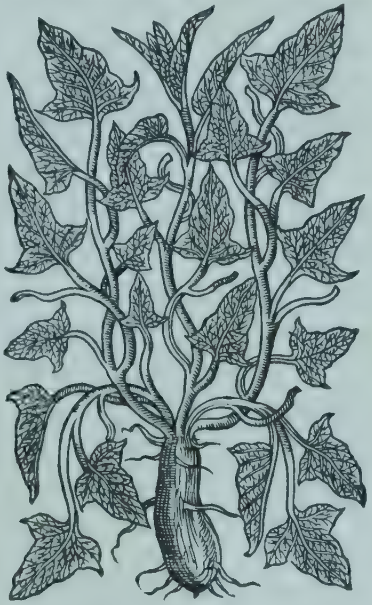

Figure 2—*The sweet potato. From Gerard's* Herball, *1597. It is often mentioned in Jacobean literature.*

By the close of that century the potato had become much cheaper, and through careful selection good varieties were produced. These won public favour, and consumption advanced steadily. After 1780 in Britain the number of industrial workers grew rapidly, and there was an increasing shortage of wheaten flour. By the end of the century the average man had at his disposal but two-thirds of the wheat he had enjoyed at its beginning. An additional source of food was necessary, for wars and the growth of population caused the price of bread to soar. Within two decades the potato was a necessity in Britain's larder, and was hardly less essential in the rest of Europe. By 1800 it had come to stay as a staple ingredient of European diet.

Maize (*Zea mays*). Columbus records that, during his first visit to Cuba (November 1492), he saw a 'type of grain like millet, which they call *maize*, which tasted very well when boiled, roasted, or made into porridge'. The Indians had cultivated maize for centuries and knew several species of it; they had a host of methods of turning it into palatable foods, and used the rest of the plant for a diversity of purposes [3]. The Spaniards gave it the name of *panizo de las Índias*, from its resemblance to millet, *panizo*.

Maize was soon taken to Europe. The first importations were from the West Indies, others from Mexico and Peru followed. At first the plant was grown in European gardens as a curiosity, but within a few years it had spread over southern France, through Italy and the Balkans, to Asia Minor and north

Africa, in which regions it rapidly assumed economic importance. Though it began to attract attention in southern Europe by the beginning of the sixteenth century, it remained in the north a poor competitor with other cereals, for climatic reasons.

The great navigator Magellan (? 1480–1521) seems to have introduced Caribbean and Mexican varieties of maize into the Philippines and the East Indies, whence they reached the Asian mainland. Varieties from Brazil were brought to west Africa and thence to India by the Portuguese. Maize became an important commodity for the slavers plying from Africa to the West Indies, though it was never a specific unit of cultivation in Africa or Asia. Its rapid spread to Turkey and the Near East caused confusion in botanical circles. Thus Fuchs, who gives the first good picture of the plant in his famous herbal (1542) (figure 3), says that it came from Asia and calls it *Turcicum frumentum* or 'Turkish corn' [4].

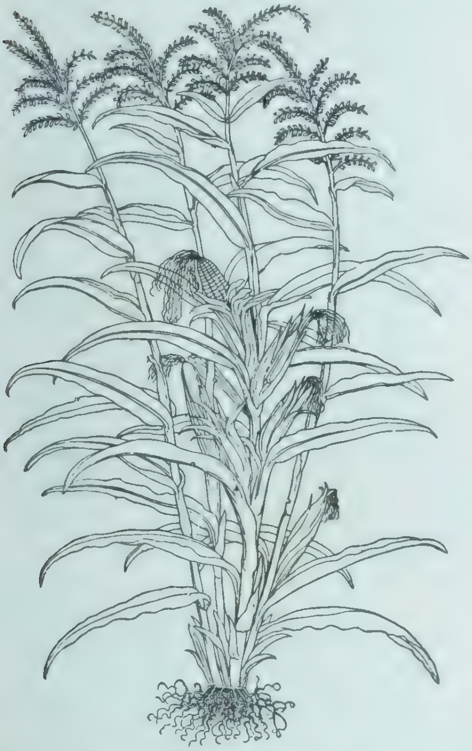

FIGURE 3—*Maize. From Fuchs's* Historia stirpium, *1542.*

That in the earlier references to maize little attention was given to its use and preparation was a factor in the tardiness of its acceptance. No mention was made of 'green corn' as food, or of the methods of removing the hulls of the grain with lye and lime, though a few explorers actually recorded these American Indian practices. While European medical and agricultural writers neglected the sound Indian recipes, valuing maize only for its imaginary medicinal properties and treating it as a kind of wheat, it was naturally unesteemed. Thus when the Spanish physician Casal described pellagra (1730), now recognized as a vitamin-deficiency disease, he believed it to be a toxic effect wrought by changes in maize caused by the climate of Europe. Yet maize did become a popular food in south-eastern Europe in the sixteenth century, eaten mostly in the form of a porridge called *polenta*. Its excellent qualities were not fully recognized until late in the nineteenth century.

Rice (*Oryza sativa*) was a crop well known in the Middle Ages, for the Muslims brought it to Spain in the eighth century. Its cultivation demands irrigation and a hot climate, hence it was successful only in southern Europe. Rice-growing was introduced into Italy during the sixteenth century, and about 1700 it reached South Carolina, whence it spread widely in the Americas.

Buckwheat (*Fagopyrum esculentum*) had been grown on a larger scale since 1400, and its cultivation spread during the sixteenth century when it was found profitable though precarious on peaty soils. *Oil-producing plants* like rapeseed and coleseed (colza), varieties of *Brassica napus*, grew in favour as it was discovered that they yielded not only oil but cattle-fodder in the cakes left after pressing. They did not acquire full importance, however, until well into the nineteenth century.

Tea (*Thea* spp), *coffee* (*Coffea* spp), and *cocoa* (*Theobroma cacao*) were never grown in Europe, but their introduction made an important change in European diet and drinking habits. The oldest of these new beverages, tea, was popular in China about 150 B.C. but did not reach Japan until the ninth century A.D., to become its national drink by 1300 [5].

The first shipment of tea was brought to Europe by the Dutch East India Company in 1609; some of it was sold in London for £3 10*s* a pound. Ten years later the price had dropped by half. By 1636 tea was drunk in Paris, and by 1646 the English East India Company was importing it. Though heavily taxed its price dropped to about 20*s* a pound by 1689. In that year imports reached a total of 20 000 lb. By 1750 tea had become sufficiently cheap to be a popular beverage.

Tea was still drunk in the Chinese fashion as a weak infusion, largely for its supposed medicinal qualities. Thus Samuel Pepys writes (28 June 1667): 'Home and there find my wife making of tea; a drink which Mr Pelling, the Potticary, tells her is good for her cold and defluxions.' In Holland the distinguished physician Cornelius Bontekoe (d 1685) prescribed 100 to 200 cups a day and drank tea himself day and night. Tea was never greatly favoured in Italy, France, and Germany, where coffee became the popular beverage [6].

Coffee was first harvested in Ethiopia (1450). It is said that a shepherd noticed that his goats remained awake all night through eating the berries of a certain shrub, and that it was found that an infusion of these berries yielded a drink which did indeed chase away sleep and suppress appetite. Early in the sixteenth century seeds were sent to Aden, whence coffee spread to the Muslim world. The Venetians entered the coffee-trade about the end of the century. Prospero Alpini of Padua (1553–1617) first described the plant.

Coffee-drinking was an established habit in the Near East by this time. It had reached Paris by 1643, and less than fifty years later there were already 250 coffee-houses in the city. In Germany neither staunch opposition nor punishments could stop its advance. In England the first coffee-house was opened by a Jew called Jacob at Oxford in 1650. Others appeared in London, and at Cambridge and other towns, to become meeting-places for literary, artistic, scientific, and commercial groups.

Meanwhile Europe was making herself independent of the Near East for her supplies of coffee by starting plantations in tropical countries. Nicolaas Witsen (1641–1717), burgomaster of Amsterdam, prompted the East India Company to have coffee-shrubs taken to Java. In 1700 they were common around Batavia, and a strong plant was sent back to Amsterdam, whence seedlings went to Surinam to start the cultivation of coffee in the New World. Brazil obtained its first coffee-plants from Amsterdam and Surinam.

Chocolate and *cocoa* were products of the New World [7]. Cortez found the cacao-bean highly regarded by the Aztecs of Mexico as being very nutritious and beneficial to their health. Chocolate reached Spain in 1520 in the form of slabs and tablets. The 'chocolatl' of the Mexicans had been compounded of cacao-beans and other seeds, but the Europeans brewed their new drink from cacao-beans only. It reached Flanders and Italy about 1606. The first chocolate-house was opened in London by a Frenchman in 1657, where the 'excellent West India drink called chocolate' was sold both raw and prepared. Pepys tells us that he first drank 'jocollate' at a coffee-house in November 1664. In England as in France the drink became popular only when abundant supplies of cane-sugar were available, and for a long time it remained a luxury. In the next century Linnaeus (1707–78), knowing the Aztec legend of its divine origin, gave the plant the generic name *Theobroma* ('food of the gods'). As with tea and coffee, Europeans soon began the cultivation of the cacao-bean in their tropical colonies.

These new beverages all demanded sweetening agents. Europe had largely relied upon honey and must (unfermented grape-juice) in the Middle Ages, for sugar remained a rare and expensive importation from the Near East [8]. During the later Middle Ages the consumption of sugar in Europe rose steadily, and honey and must were gradually replaced by it. The cane was introduced into southern Europe, and sugar became an important article in the trade of Genoese and Venetian merchants, who brought it from Cyprus, Syria, and Egypt (vol II, p 372). During the age of discovery the sugar-cane was taken to Madeira and the Canaries; later it reached Central and South America, and in the early seventeenth century it was first grown in the West Indies (figure 4). These islands became in the seventeenth and eighteenth centuries the main sources of supply for the European market, the factories being built on the Egyptian model.

The habit of taking sweetened drinks and eating sweet puddings and pies became more common during the seventeenth century, and by 1700 the price of sugar had fallen to 6*d* a pound, or less. Raw sugar was imported into England, Holland, and other European countries, and there refined for the local market.

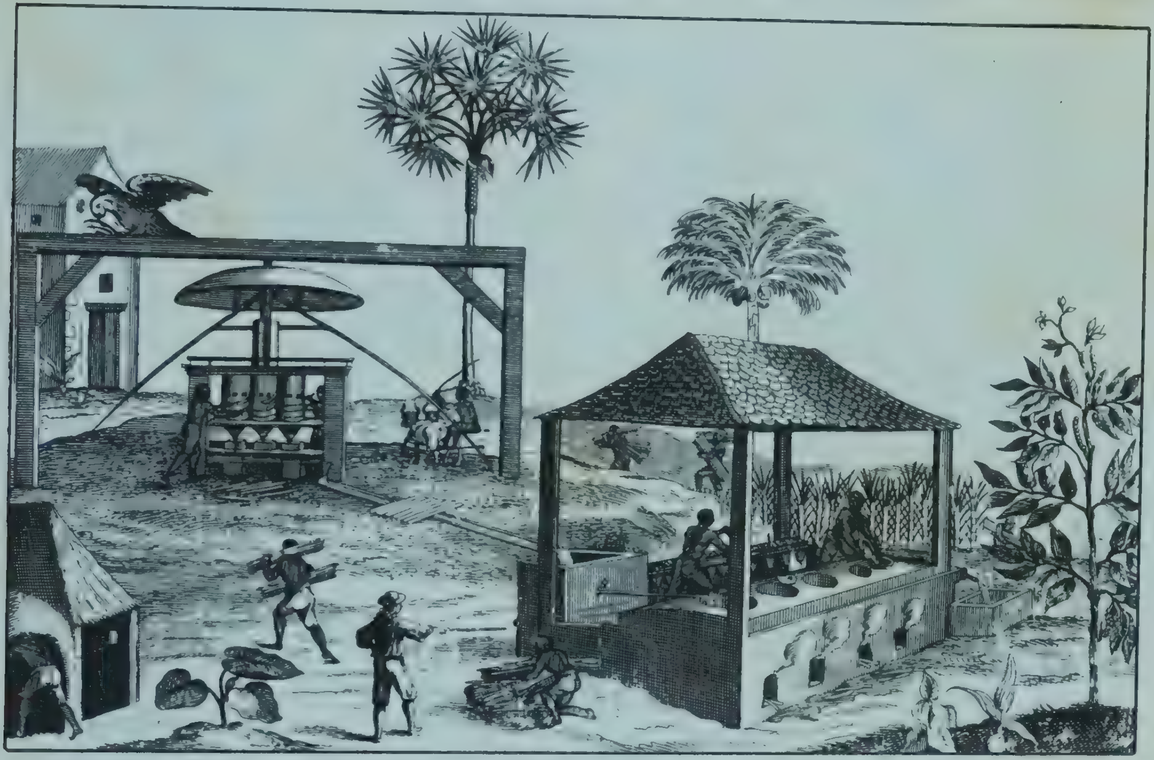

FIGURE 4—*West Indian sugar-factory.* (Left) *Vertical roller-mill crushing the canes;* (centre) *channel to the first boiler, where the juice was reduced and skimmed;* (right) *boiler-house. In the second boiler the sugar was purified with lime and egg-white, in the third and fourth it was concentrated to permit crystallization. 1694.*

The original process of making sugar as used by the Arabs[1] was simple. The pieces of sugar-cane were expressed between rollers (sometimes driven by windmills or water-wheels) and then often boiled with water to obtain a second extract. The expressed juice was skimmed, filtered, and boiled down to a brown-black syrup, scum and dirt being skimmed off at intervals. From this syrup loaves or cones of raw brown sugar were obtained (vol II, figure 340). The Egyptian refineries, however, introduced more sophisticated methods of treatment.

In the European refineries a solution of the raw sugar was refined by adding lime-water and blood; the mixture was boiled and skimmed until no more scum was formed and the boiled solution was clear. It was then filtered through cloth and evaporated as quickly as possible until a sample showed the correct consistency. The viscous mass was transferred to the crystallization-vat, mixed with other portions, and then allowed to crystallize in pottery moulds. Refining was not further improved until the nineteenth century when proper evaporation, heat-economy, and refining with charcoal and decolorizing earths were introduced. By 1800 about 150 000 tons of sugar were consumed annually in England—fifteen times the amount consumed in 1700.

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[1] The word sugar is derived from the Arabic *sukkar*, cognate with the Greek *sakchar*.

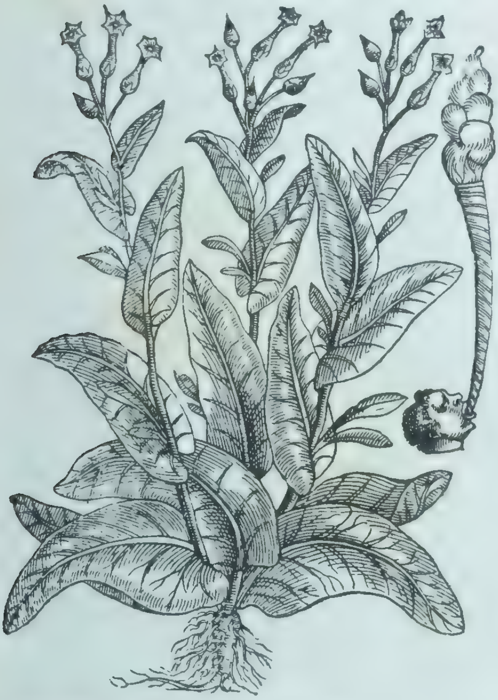

Figure 5—*The tobacco plant. From a herbal of 1570.*

Tobacco (Brazilian or Carib *tabaco*) also came from the New World, and its cultivation was soon of economic significance [9]. When Columbus first landed the natives offered him some leaves which they clearly considered very valuable. On reaching Cuba (2 November 1492) he observed men and women smoking 'cigars' of a weed called 'tobaccos' there, but elsewhere known by other names. Before 1560 tobacco plants (*Nicotiana* spp) were cultivated in the 'physic gardens' of the botanists and herbalists in western Europe (figures 5, 6) and tobacco reached England about 1565. The Spaniards brought its cultivation to the Philippines about 1575, whence it spread to north and west. The African natives developed a great appetite for tobacco in the seventeenth century, when it became an important article of currency in the slave-trade.

In Europe, tobacco was first used as a medicinal herb. André Thevet (1502–90) described how the natives of Brazil used it to 'loosen and carry off the superfluous humours of the brain'; he brought seeds to France in 1556 [10]. Jean Nicot (? 1530–1600) observed it at the Portuguese court, and Jacques Gohory (d 1576) of Paris gave tobacco repute as a cure-all. Not until the end of the seventeenth century did it lose its medical interest. Cultivation, first of *Nicotiana tabacum*, then of *N. rustica* (which was better suited to the European climate), began in Spain in 1558. Thence it spread to Italy, Turkey, the Balkans, Russia, and farther east. In Europe it appears here and there as a cash-crop by the end of the sixteenth century. Word of the new plant was brought to England in Thomas Harriot's account of Virginia (1588) after the first abortive attempt to settle there[1] [11]. The emigrants had brought back tobacco plants (*N. rustica*) from Virginia to Gloucestershire in 1586. Success for European pioneers of tobacco-culture in Virginia itself came only in 1612, when John Rolfe (1585–1622)[2] brought seeds from the Spanish plantations farther south and when selection of proper species prevailed. Exports of Virginian tobacco to England, where it was in high demand as a substitute for the expensive Spanish product, soon increased. The English Navigation Acts protected the Virginian tobacco-farmers, who by the early eighteenth century had established an important industry there. Correspondingly, the growing of tobacco in England was prohibited.

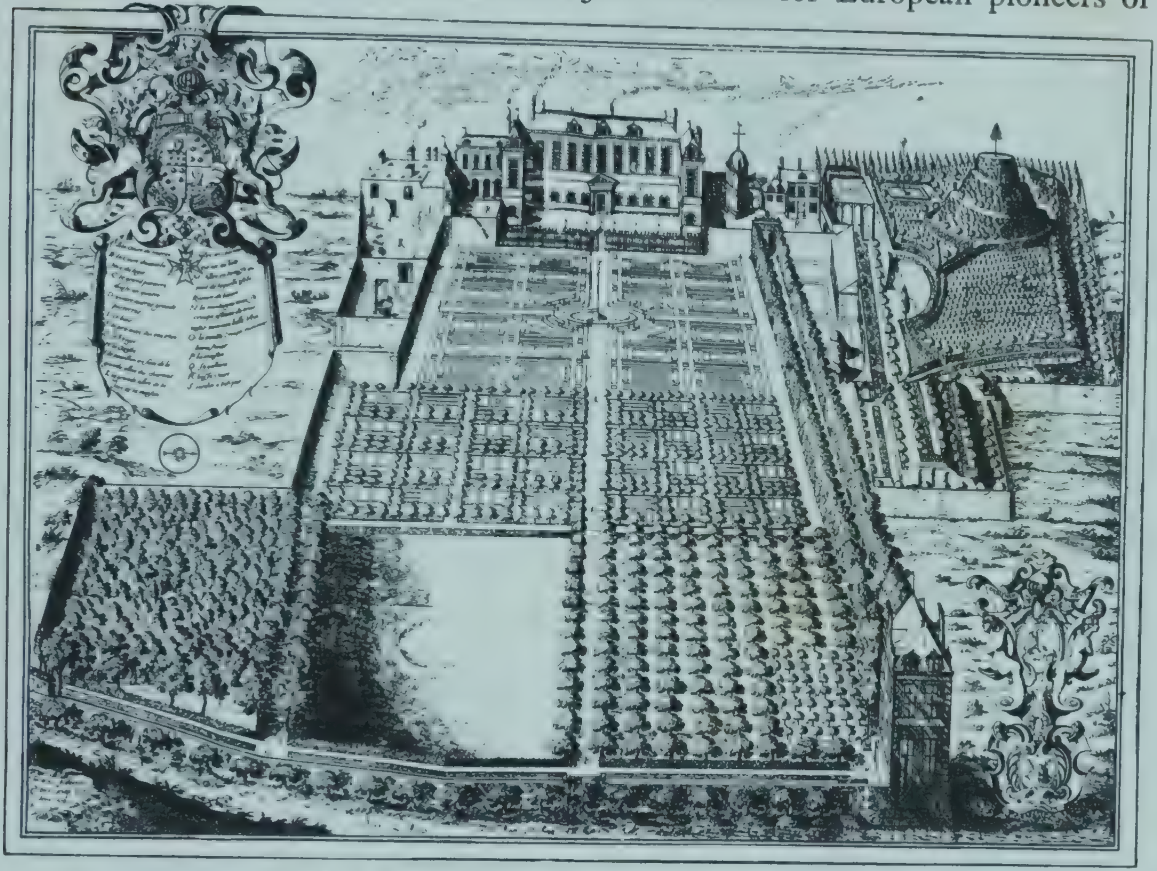

FIGURE 6—*Botanic Garden in Paris, the* Jardin des Plantes, *in 1636. The herbs were grown in the formal beds.*

The habit of smoking tobacco met with formidable opposition, headed in England by James I's 'Counterblast to Tobacco' (1604). The war against it raged until 1650 and later in some countries, but neither western nor eastern rulers could eradicate the taste for tobacco which later justified itself in their eyes as a new source of revenue. Smoking went out of favour in polite society in the eighteenth century, when snuff-taking was the rage, and even in the nineteenth it was regarded as a peculiarly masculine vice.

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[1] Thomas Harriot, mathematician and astronomer, was born at Oxford in 1560 and died at Isleworth in 1621. He was a friend of Sir Walter Ralegh and of the 'Wizard Earl' (Henry Percy, ninth Earl of Northumberland).

[2] Husband of Pocahontas.

Snuff-taking dates back to 1558, when powdered tobacco-leaf was introduced into Portugal; the practice was supposed to have a medicinal value. Jean Nicot, the French Ambassador there, sent some seeds to Queen Catherine de Medicis, and so snuff came to France. The habit evidently commended itself, for the Papacy had to prohibit snuff-taking in church. The ground tobacco was commonly adulterated with other herbs, charcoal, and soda before it was sold as snuff. An elaborate social etiquette was founded upon the snuff habit, which for a time consumed a large quantity of tobacco and still has numerous votaries.

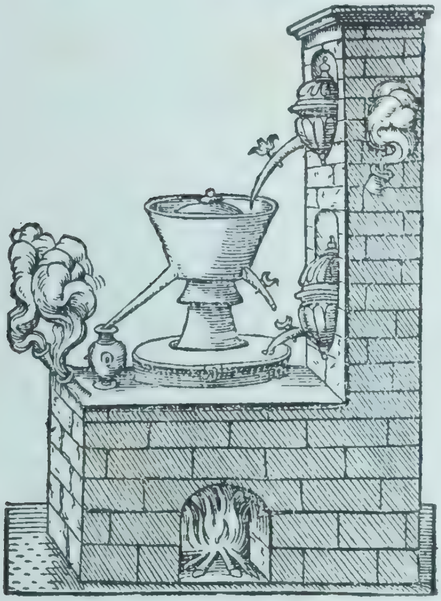
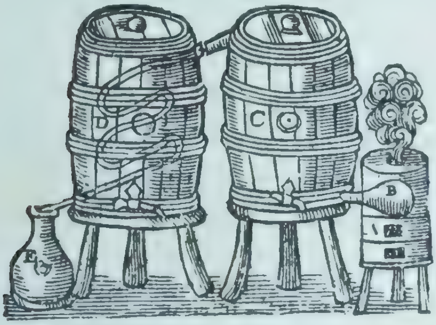


FIGURE 7—*Distilling-apparatus.* (Above) *Brick-built still in which the alembic head is cooled discontinuously by a water-trough. 1567.* (Below) *Cask still; to save metal, only a small part of the liquid in the still* C *is heated directly by the furnace in the copper boiler* B. *The distillate flows through the worm-cooler* D *in a cask of water. 1651. Such illustrations were very frequently reprinted for over a century.*



II. ALCOHOLIC DRINKS

There was little change in the manufacture of alcoholic drinks in this period. Beer won the market formerly enjoyed by cheap wines, and imports of wine from Spain and France into northern Europe declined with the imposition of tariffs, navigation acts, and other measures tending to reduce freedom of trade. Such legislation promoted the consumption of locally produced beer, cider, and other drinks. Most imported wines were drunk from the wood, bottling, if desired, being carried out by the consumer or vintner. Cork stoppers were not widely used before the late seventeenth century, when the custom of bottling and laying down special wines began. Apart from the introduction of hops during the late Middle Ages (vol II, p 140) no important change took place in brewing and malting. The ordinary weak home-brewed beer was a harmless and healthy drink in an age when water was commonly impure.

Spirits were now competing seriously with wine and beer in many countries. Many kinds of 'aquavite' were distilled from cheap wine or fermented corn, with secret mixtures of herbs and berries. This gave rise to much abuse until such national organizations as the Distillers' Company (1638) and others drew up regulations for the trade. Gin was introduced into Holland by German soldiers from Hanover serving in the wars of liberation against Spain; thence it went to England and Ireland. In early eighteenth-century London the sale of cheap gin under the sign 'Drunk for a penny, dead drunk for twopence' became a social evil, savagely depicted by Hogarth (plate 2 A). Its destruction of the energy and morals of the 'labouring poor' was prevented only by the imposition of an excise. Similar events occurred in other great cities. Whisk(e)y[1]—the usquebaugh[2] of the Irish bogs and Scottish moors—made its way into genteel society in Britain as did schnapps in Holland. Hot punch warmed a cold winter's gathering, and the new practice of fortifying wines with brandy (vol II, p 142) contributed to the popularity of sherry, madeira, and above all port.

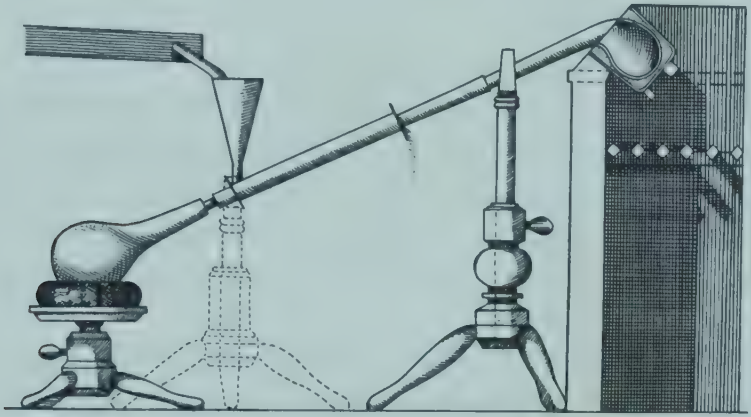


FIGURE 8—*von Weigel's still with counter-current cooling, 1773. The distillate flows down from the retort on the right to the receiver, while the coolant flows upwards through the water-jacket.*

There was some empirical but no scientific development of distillation and distilling-apparatus (figure 7) [12]. There were further attempts to develop proper cooling of the alembic and the distillate. Such operations as repeated boiling and rectification received some attention, and apparatus for these operations was developed, but little progress could be made while the theory of heat

[1] By a useful convention, whisky is Scotch and whiskey Irish.

[2] Gaelic *uisge beatha*, water of life. Hence 'whisky' equals 'water' (cf *vodka*).

was inadequate to guide design and operation. The principle of continuous counter-current cooling was introduced by von Weigel (1773) (figure 8) and Magellan (1780), and duly led to the famous Liebig condenser (1830). Steam was already used in the distillation of essential oils from flowers and fruit, and distillation techniques were now applied to the manufacture of sulphuric, hydrochloric, and nitric acids, as well as to the preparation of wood-tar (ch 25). The distillation of spirits was still crude. The distillate was highly contaminated unless redistilled several times, but a check on purity was provided by use of the hydrometer (p 22).

III. NEW AGRICULTURAL TECHNIQUES

The employment of new agricultural techniques, notably in the seventeenth and eighteenth centuries, was only partly a result of the cultivation of new crops [13]. It was more often caused by local economic changes, which varied all over Europe. There was an increasing endeavour, reflected in the literature of the time, to encourage the best farming methods and to discover their scientific foundation.

In Germany progress was halted by political causes. The peasant wars of the sixteenth century ended disastrously, and the Thirty Years War (1618–48) again brought devastation to central Europe. Many decades passed before peasant agriculture was as prosperous as it had been at the close of the Middle Ages. In 1700 real wages were still at only about half the standard of those of 1500; much of the population lived on the margin of starvation. Yet the cultivation of winter fodder for cattle profited by the slow introduction of clover and lucerne from Italy by way of Flanders, though 'artificial grasses' remained uncommon until 1750. The many cattle that could not be fed through the winter had to be killed in the autumn and pickled or smoked. Fewer pigs were bred as deforestation proceeded, owing to the reduction of their food-supply; sheep took their place. More pigs were raised again when the potato was introduced. Oil-yielding rapeseed and colza came to central Europe very slowly and were not important crops until after 1750. The farmers of that region, as elsewhere, were usually better fed than the poorer townsmen, who had already suffered through the withdrawal of trade from Italy and Germany to the Atlantic seaboard, following the discovery of America and new routes to the East.

There was little uniformity in European farming methods, for even in France, a more advanced country, striking contrasts could be observed. The neighbourhood of Paris and west and north-west France were areas of *petite culture*. In Picardy the methods differed greatly from those current in Artois and Flanders.

Even viticulture had its traditional local variations of technique. The penetration of the potato was slow, becoming effective only at the end of the period. Maize was cultivated with some success in the south-west. It was not only an important food for the poor but, together with clover and other new crops, was used as cattle-fodder. The eighteenth-century physiocrats, who believed that cultivation of the land was the sole real foundation of wealth, glorified the farmer and his work but directed little effort towards the practical improvement of farming. Most French farmers persisted in the use of medieval methods; improvements were merely local. France thus remained a land of fallows and scattered strips, of scrub animals and clumsy implements. The sound initiation of agricultural writing in the sixteenth century by such original authors as Charles Estienne (1504–64) and Olivier de Serres (1539–1619)[1] was not followed up [14]. The attempt to improve French agricultural technique was begun only just before the Revolution, and in imitation of what had been achieved in England.

The story of farming in the Netherlands is completely different. Treatises on farming were very inadequate, failing even to describe the work of draining and reclaiming farmland for which the region was famous. Here the practice was that of 'horticulture transferred to the field'. The Netherlands were in this period the most densely populated area in Europe. They flourished on their great carrying-trade—wine and salt from France and Spain were traded for the timber and corn of the Baltic. Regular imports of corn were needed to feed the people. They grew flax for the linen-industry, madder, weld, and woad for dyeing, barley and hops for brewing, hemp for ropes, and tobacco. The industrial crops were mostly grown in the western provinces and some were exported. The United Provinces specialized in horticulture, market-gardening, and fruit-growing. These required extreme care and the application of fertilizers, which were obtained from the stock-raising areas and the towns. Ashes, compost, night-soil, and oil-cakes from the mills were all used as manures. Sheep-manure and pigeon-dung were in heavy demand, notably by tobacco-growers.

Market-gardening, arboriculture, and bulb-growing increased greatly in importance during the seventeenth and eighteenth centuries, during which the old alternation of crops was replaced by a three-year crop-rotation or even by a cycle of nine years in which clover played a part. Bed-cultivation and row-cultivation were typical of these regions. Rapeseed was largely replaced by colza during the sixteenth century, yielding cattle-fodder. Potatoes spread slowly but did not gain much importance until their value as foodstuff and fodder was understood, after the famine of 1740–1.

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[1] de Serres introduced the cultivation of the mulberry in France.

Certain improvements in types of plough were made in Flanders and Brabant, and new marking-tools and seeding-horns were proposed. Attempts at constructing a sowing-machine (1770) failed, but a winnowing-mill was introduced (1727) from China. The churn-mill for the manufacture of butter is first mentioned in 1660. Cattle-breeding was not yet rationalized, though the standard was already high.

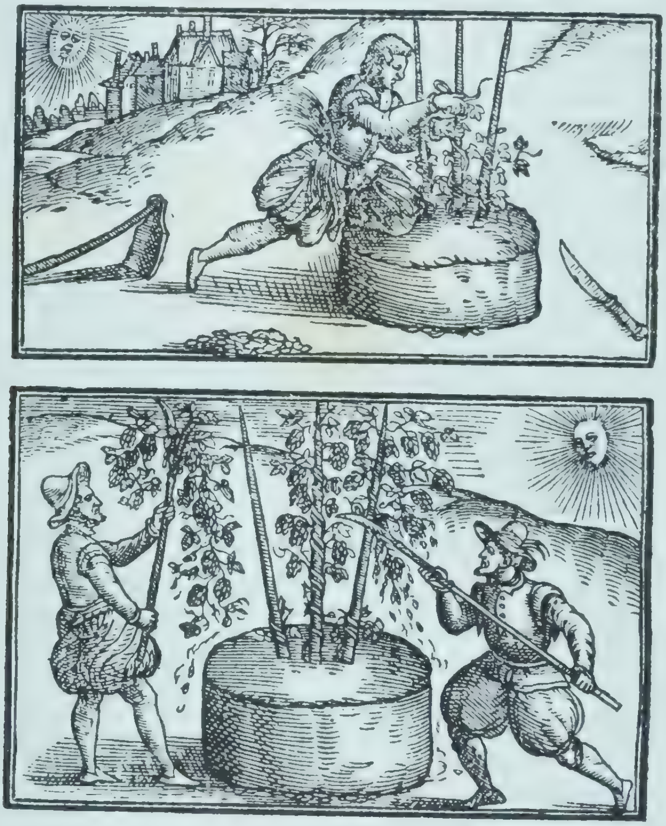

FIGURE 9—*The hop-garden.* (Above) *Tying the young hop-vines.* (Below) '*The best and readyest way to take the hoppes from the poales.*' *1574.*

Sixteenth-century England saw a vigorous development of farming. The 'floating' of water-meadows was introduced, market-gardening began to develop slowly but steadily, and there was a revolution in rural housing. Many new books on farming were published, such as Fitzherbert's 'Boke of Husbondrye' (1523) and Tusser's 'Hundreth good pointes of Husbandrie' (1557). The latter also dealt with gardening, grafting, planting of trees, cultivation of hops (figure 9), and management of poultry and cattle. However, English agricultural literature up to 1700 was wholly empirical and could have no proper scientific basis. Most of the new books led away from subsistence farming and were inspired by the methods used in the Low Countries. The investigations begun by the Royal Society after 1660 failed either to produce a nation-wide survey, or, despite a few experiments with turnips and clover, to promote the general adoption of new crops and methods.

In England as in Holland the East India trade stimulated the rise of a class of gentleman-farmers who had invested their commercial profits in country estates. Rents trebled and purchases of land doubled between 1600 and 1688. Though the price of corn fell, the acreage under it increased. Agrarian conditions improved through the better adjustment between tillage and wool-production, and through greater stability of employment on the new estates. Market-gardening became more important as the size and wealth of the towns increased. The old bailiff-farming practically disappeared.

After this incubation period the early part of the eighteenth century may well be called the age of the innovators. The old forms of crop-rotation with fallow periods had been abandoned by landowners and tenants in favour of legume-rotation and field-grass husbandry, under the influence of late medieval town economy. This was notably the case in the southern and eastern districts of England. Enclosure of the medieval open fields was a cause of rural depopulation, but on the other hand the pioneers of the 'New Husbandry' and scientific rotation were now active. Jethro Tull (1674–1741) invented the seed-drill, pulverized the soil to cultivate without manure, and introduced the horse-hoe from Languedoc. Charles Townshend (1674–1738) introduced the Flemish method of cultivating turnips, clover from Spain, and manuring by marling. Burgundian and other French grasses suitable for pastures were imported. Arthur Young (1741–1820) and William Marshall (1745–1818) sought to improve British agriculture by educating the farmer in the scientific principles of farming. Robert Bakewell (1725–95) and the Duke of Bedford (1765–1805) effected great improvements in cattle by systematic stock-breeding. Famous gentleman-farmers like Thomas William Coke of Holkham (1752–1842), Lord Somerville, and Sir John Sinclair took part in this movement, which was to bear fruit between 1770 and 1850 and attain the finest balance between tillage and cattle-breeding before the introduction of specialized intensive farming later in the nineteenth century.

IV. MILLING

The production of flour was a major industry, employing most of the available water-wheels and windmills [15]. The relatively simple machinery embodied much empirical knowledge. Thus the mill-stones had to be obtained from special quarries. Local stone was used, but English millers preferred those obtained from Andernach on the Rhine, and the French millers those from La Ferté-sous-Jouarre and Bergerac, near Paris, which were even exported to America. Good grinding demanded that the runner-stone be very exactly balanced over the bed-stone. Usually it was balanced by lead poured into four symmetrically sited holes drilled in the top of the runner-stone. Adjustment of the distance between the stones was effected by screws.

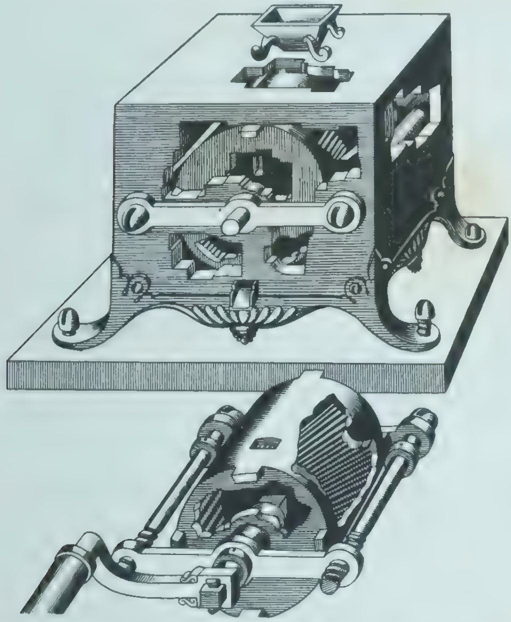
FIGURE 10—*Ramelli's portable iron roller-mill for grinding flour. Both the roller and the interior of the drum are grooved; they are slightly tapering, so that adjustment of the long screws alters the fineness of the grind. The grain is placed in the little hopper and the flour emerges from the spout. 1588.*

The floury part of the kernel had to be ground to the finest possible powder without overheating. Hence the grooves of a dressed stone served not only in cutting but in ventilating the meal as it passed outwards towards the circumference. As the American Oliver Evans expressed it: 'A dull stone kills or destroys that lively quality of the grain, that causes it to ferment and rise in the baking; it also makes the meal so clammy that it sticks to the cloth and chokes up the meshes in bolting.' The dressing of the stones was done by itinerant craftsmen.

During the sixteenth century there were attempts to make milling more simple and efficient. The Emperor Charles V, after his abdication and retirement into a monastery (1556), is said to have invented, with his watchmaker Turriano, a roller-mill 'small enough to be placed in the sleeve of a monk's gown'. Such a roller-mill figures in Ramelli's book on machines (figure 10) [16]. Ramelli's mill has a rotating roller with spiral grooving. The combination of the roller with its suspension inside the casing, the spiral corrugations, the provision of a hopper, and the arrangement for bringing the two grinding-surfaces together, reveal this design as far ahead of its times. Another roller-mill was illustrated by G. A. Böckler in his *Theatrum machinarum novum* (1662) (figure 11) [17]. Its roller was eccentric to the concave block near which it rotated; thus grinding took place along a straight line rather than over the whole surfaces as with mill-stones. The meal passed into a bolter (sieve) agitated by the crank rotating the roller. Böckler's method is that of the modern mill, in which a second rotating roller takes the place of his concave block. We do not know how far these ideas were applied in practical milling before the end of the eighteenth century.

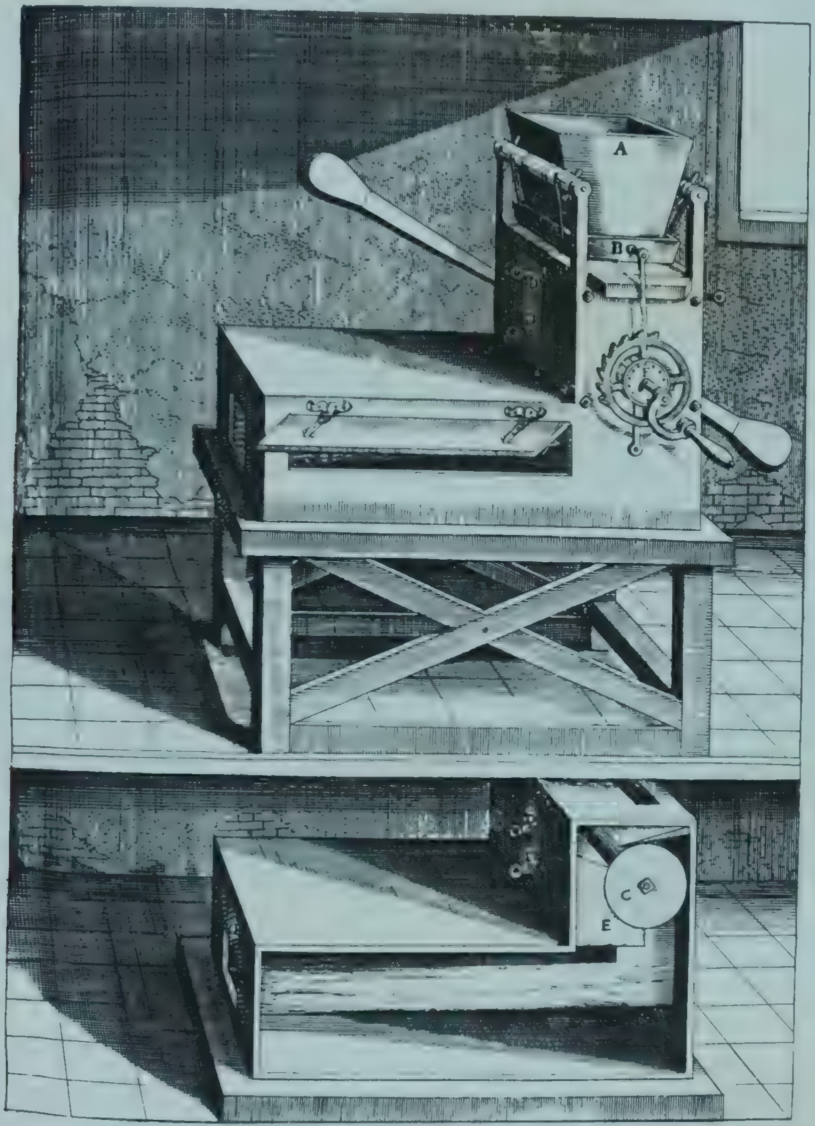

Figure 11—*Böckler's roller-mill.* (A) *Hopper;* (B) *sieve agitated from the drive;* (C) *roller;* (D) *adjusting screws;* (E) *fixed concave block. 1662.*

In the second milling-operation progress was also very slow. The meal was crudely sifted to divide the fine flour from the grits, the sieves being square box-like structures shaken by hand. Soon such sieves were fitted into a kind of hand-agitated bolter, as shown by Jerome Cardan in his *De subtilitate* (1550), which permitted four separations.

The mechanization of bolting began with Boller's proposal to use mill-power to shake the sieves (1502). An early illustration of mechanical bolting is given by Verantius in his *Machinae novae* (Venice, *c* 1595) in which a lever is struck by a lantern-wheel and so agitates an inclined trough covered with cloths of different meshes (bolters) (figure 12). Bolting-cloth was an extremely hard material of even weave. It was originally of linen or cotton, but during the eighteenth century silk was often used with up to 100 threads an inch, and therefore of very fine mesh. These devices were still hand-operated. Cylindrical bolters with power-operation were designed by Ramelli (1588) (figure 13) and Charlemagne (1793). Auxiliary drives were used in many mills to hoist the unground grain, and for other purposes, but the introduction of such mechanical refinements as bolters and hoists was retarded by the slow improvement of gearing and the lack of proper design in water-wheels, windmills, and other machinery. Above all there was still no urge for the large-scale production of flour, which

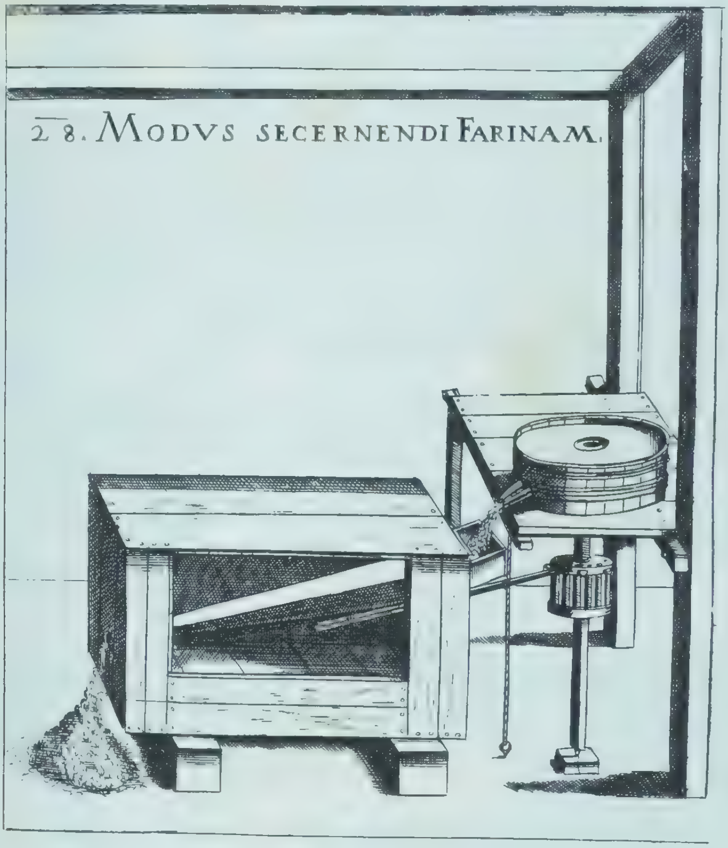
28. MODVS SECERNENDI FARINAM.

FIGURE 12—*Verantius's mechanical bolting-device; the bolter is agitated by a lever struck by a pinion on the mill-stone drive.*

was milled for local use and seldom carried over long distances owing to the great cost of transport. Much grain, however, was carried by sea. As the prime movers slowly developed, the idea of powered factories sprang up here and there; thus the Swedish metallurgist Polhem built (1700) a water-driven factory to manufacture a wide range of metal tools and objects. He employed rolling- and shearing-machines and a variety of specially invented devices. The mechanization of flour-production awaited the work of Oliver Evans (1795), who designed the first automatic mill for the mass-production of flour, using power-driven roller-mills and cylindrical bolters.

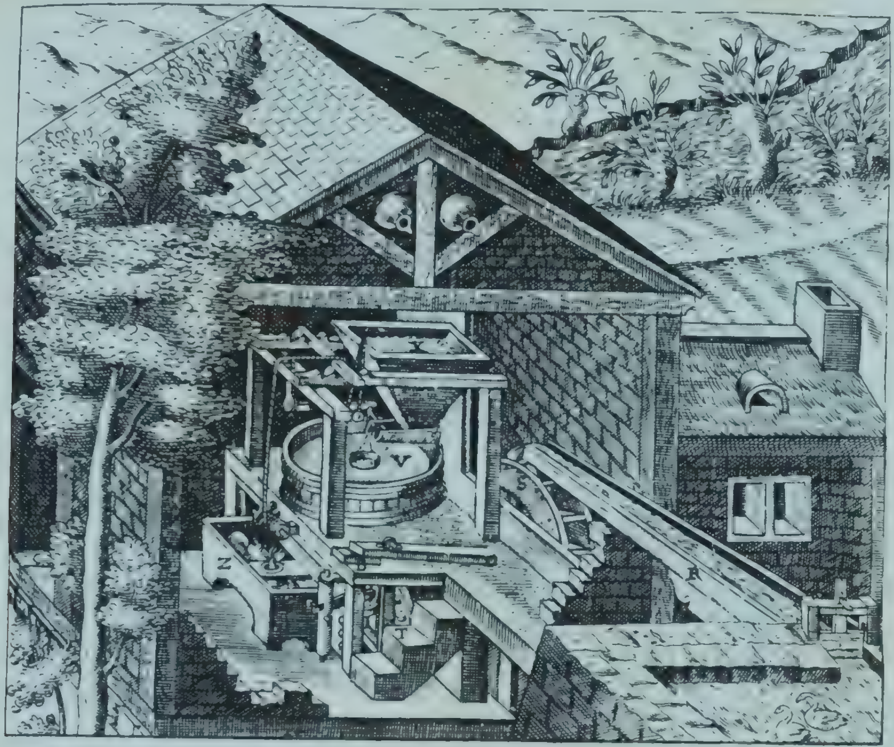

FIGURE 13—*Water-driven corn-mill with mechanical bolting-device* (lower left), *on which the flour falls from the stones. The bolter is actuated by a lever from the main driving-gear. Ramelli, 1588.*

V. PREPARING, TESTING, AND PRESERVING FOODSTUFFS

Cookery-books were published soon after the advent of printing, one of the earliest being the English 'Boke of Keruynge' (carving) of 1508. They helped to spread skill in the more refined ways of preparing food for the table, and in the cooking of the newly cultivated vegetables. Changes in eating-habits also occurred. Whereas in the Middle Ages two meals a day were generally considered sufficient, four were not uncommon in the sixteenth century. The main meal was usually at noon, followed by a supper at about seven or eight o'clock in the evening, but by the eighteenth century gentlefolk had their main meal in the late afternoon, a light lunch preceding it and tea following. The use of the spoon spread quickly in the sixteenth century. The fork (normally two-pronged) was used in the Middle Ages to hand pieces of food to guests or table-companions, then the old-established Italian custom spread, in the seventeenth century, of using it to bring food to the mouth. An Englishman who saw this custom in Italy in 1608 and tried to introduce it at home was nicknamed *furciferus* (fork-bearer). At the Austrian court in 1651 food was still eaten with the fingers, but by 1750 the fork had become fashionable through imitation of French manners. Three- and four-pronged forks appeared in the seventeenth century. At the same time the guests were also provided with knives, for in earlier days everybody brought his own knife and spoon or fork. Slices of bread had served as plates for centuries, but wooden, pewter, and pottery table-vessels became common in the sixteenth century. The industries—especially those of pewter, pottery, and glass—supplying table-ware were correspondingly enlarged to meet the growing demand. Glass drinking-vessels became common about 1650.

A few new inventions entered the kitchen. Roasting was a major operation of cooking and therefore spits were important devices. Early handbooks on machinery show weight-driven spit-jacks, which became common. Though many inventors designed clockwork-jacks, the larger spits were driven by dogs turning the 'dog-drum', which was introduced about 1650 and survived into the nineteenth century. The hot air rising in the chimney was also employed to rotate a fan, which then turned the spit by means of gears (figure 14). Such 'chimney-wheels' or 'smoke-jacks' were primitive hot-air turbines. From the time of Leonardo da Vinci many famous engineers tried their hands at such devices, which, however, did not become of practical use until the eighteenth century.

The sixteenth-century fire-grate consisted of bars placed on two fire-dogs, which lifted the fire from the hearth and provided means for regulating the heat. New kinds of trivets were introduced, as were conical mullers; these vessels were filled with drink and thrust into the fire.

Progress in food-testing methods was slow, though it became increasingly important to detect adulteration in the greatly increased number of foodstuffs traded over long distances [18]. The first guardians of the food and health of the public were the 'garbellers'.[1] Garbellers had no knowledge of chemical analysis and relied on appearance, taste, and smell. Their tests were mostly empirical and dealt only with the more patent and gross forms of adulteration; rarely could they detect the more subtle impurities. New instruments such as microscopes were not systematically turned to foodstuffs until the nineteenth century. The strength of alcoholic spirits was long determined by the gunpowder test, which consisted in pouring some of the liquid on gunpowder and then trying to ignite it. If the powder burnt, the water-content of the spirit was considered to be sufficiently low. Proof-spirit would just, and only just, allow the powder to ignite.

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[1] From the Arabic *gharbala*, to sift or select.

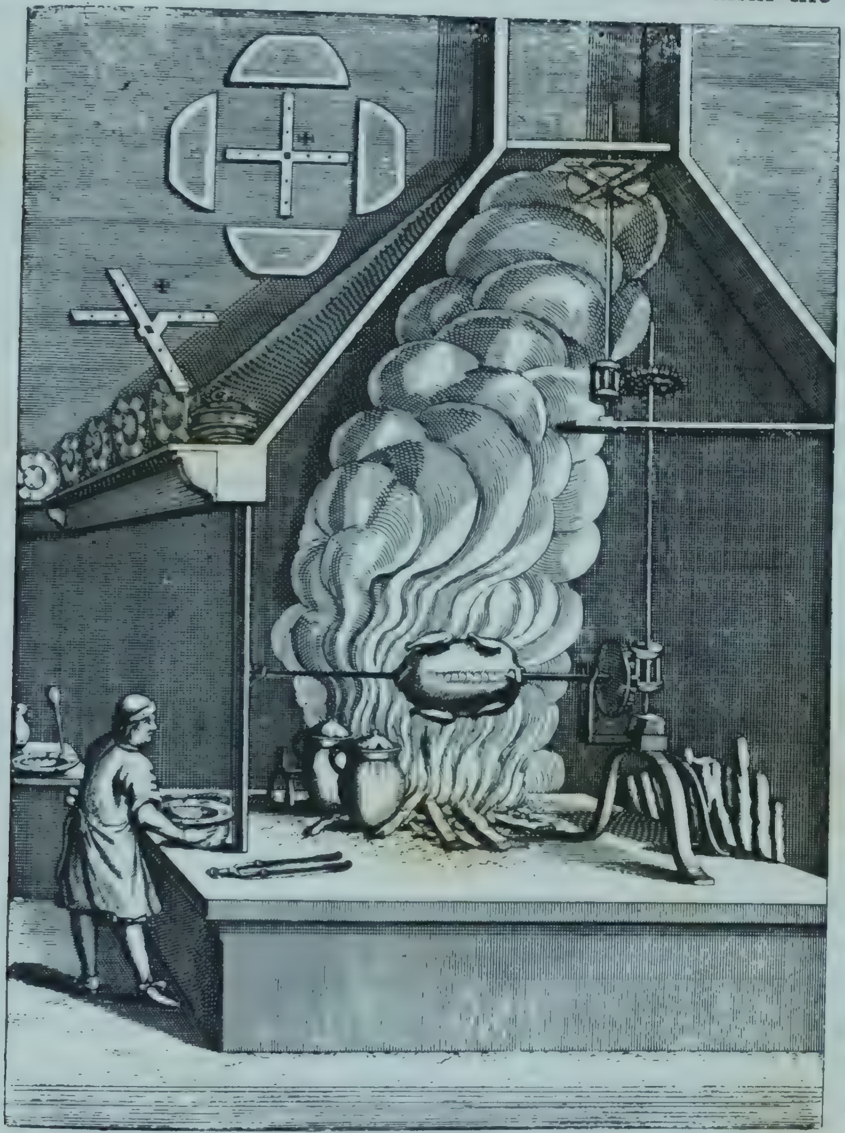

FIGURE 14—*Cooking-spit turned by a smoke-jack with a fan in the chimney. Böckler, 1662.*

The idea of using specific gravity as a characteristic of natural substances dates from Archimedes, and Arabic scientists had examined the purity of precious metals and stones in this way. The hydrometer for testing the specific gravity of liquids is also old, for the instrument was known at Alexandria in the fourth century. It was studied by many scientists of the sixteenth and seventeenth centuries. Robert Boyle (1627–91) describes a hydrometer for testing spirits, in a paper in the 'Philosophical Transactions' of the Royal Society [19]. In his *Medicina Hydrostatica* (1690) he proposes that the hydrostatic balance be used to test rain-water, wine, brandy, cider, beer, ale, and so on, using a piece of amber as the weight to be immersed. Boyle's ideas took root in many countries. Roger Clarke's 'Hydrometer or Brandy Prover' (London, 1746) was generally accepted in England. It was adjusted by adding a series of graded brass weights, and was adopted by the excise officers. George Gilpin published a series of tables giving the gravities of mixtures of alcohol and water, which were used with Clarke's hydrometer (1794).

John Dicas's hydrometer (1780) was adopted in America in 1790. In France Antoine Baumé (1768) proposed a hydrometer with fixed points marked on the scale representing the gravities of water and a specified salt solution; for solutions with a density lower than that of water the scale was simply extended below zero. Cartier adapted this idea in his hydrometer, on which the strength of alcohol could be read in 'degrees', and which was officially adopted in France (1771). A few years later (1774) Demachy published the first systematic account of the use of the hydrometer for testing alcohol, acids, and commercial fluids generally. Many other new types of hydrometer were proposed later.

The testing of foodstuffs became more effective with the rise of analytical chemistry after 1790. In 1820 Friedrich Accum (1769–1838) published his 'Adulteration of Food and Culinary Poisons', the pioneer treatise on the subject.

During these three centuries no major invention affected the preservation of food. The ancient techniques of salting, drying, smoking, and so on were hardly improved. One invention of the later Middle Ages did, however, have a marked effect on fifteenth- and sixteenth-century diet, namely an improved technique of gutting and preserving herrings [20]. Herrings had long been preserved by salting, like other fish, but this did not prevent them from going bad after some time. William Beukelszoon, a wholesale dealer in fish living at Biervliet, Flanders, invented the following procedure about 1330. As soon as the fish were caught, an incision was made near the gills. Part of the guts was removed, and the gutted fish were salted and packed in barrels. This technique was the basis of the herring-fishery, for a time a Dutch monopoly, and made possible the long-distance transportation of this cheap food (vol IV, ch 2).

The technique was invented when the fishermen of the Flemish coast were seeking independence of the English shore, and enabled them to clean and pack their fish without landing at some point nearer the fishing-grounds than their home port. Its full value was not attained at first, through the opposition of the Hanse and of the wealthier Flemish merchants.

VI. THE RISE OF DIETETIC SCIENCE

It is impossible to speak of a 'European' diet, for regional and local variations remained very great. Thus in central Europe, so often devastated by war, diet was for several centuries unvarying and barely sufficient, while conditions improved in the countries on the Atlantic seaboard. In the Low Countries, for instance, sixteenth-century diet differed little from the medieval. Meat (except perhaps pork) and milk were still unusual foods for the poorer classes, though fish—fresh, salted, or dried—was common fare. Milk, it is true, was slowly getting more popular, but butter was used by the rich only. Vegetable-growing was increasing, especially the cultivation of cabbages, carrots, turnips, onions, and leeks. Eggs were much eaten and herring was a staple food. Ale was the common drink.

During the seventeenth century several changes took place. Barley bread made way for rye or wheaten bread, the latter being a luxury. Butter became more general. Gin, at first a drink of the lower classes, became more fashionable. The ruling middle classes ate plentiful and well seasoned food; the authorities had to check their over-indulgence. Peasant diet was slightly enriched by greater quantities of milk and pig-meat, but in winter only the rich ate meat, salted or smoked. Pigeons were kept as a source of food. The potato was still virtually unknown. Diet in the army, the navy, hospitals, and almshouses was still badly balanced and generally too low.

During the eighteenth century everyone in the Low Countries ate bread of a better quality, and also potatoes. Rye bread fell into contempt as 'the fare of artisans and labourers', and wheaten bread was preferred. Gluttony was a notorious vice of both Dutch and English. Cheese and butter milk were now consumed in larger quantities, but the poor too often ate salted vegetables even in summer, and the variety was still small. Salted meat was now more common and a taste for rich, greasy food developed. Fish and eggs were still eaten in large quantities, and some fruit was consumed. Sugar became more popular as tea, coffee, and other drinks displaced ale. The diet of prisons, hospitals, almshouses, and other institutions remained inadequate.

This Dutch picture differs little from that of England. During the sixteenth century the meat-supply hardly changed. Between about 1530 and 1640 wages rose in value far more slowly than the prices of food, so that the mass of the people were less well fed during most of this period. Beans, some salted meat, bread, fish, cheese, a little bacon, and some game formed their diet; the precarious balance of their lives was easily upset by famines and epidemics. The towns had fair supplies of butter, meat, white bread, and fruit, and an increasing quantity of vegetables and fresh fish. The army and the navy seem to have been well fed.

After the general improvement in living conditions during the latter part of the seventeenth century, and despite the evil social effects of the enclosure movement and the early stages of the industrial revolution, there was a rapid increase in the population of Britain; this seems to have been associated with a general improvement in public health and diet in the eighteenth century. The death-rate declined, perhaps in part owing to the greater availability of fresh foodstuffs. There were still great distinctions between rich and poor. While the wealthy indulged too freely in rich food and wines, the diets chosen for institutions such as barracks, prisons, and almshouses, though copious enough, were unbalanced through lack of scientific knowledge. Bread, cheese, beef, and beer, nourishing in themselves, do not contain everything required for good health; there was admittedly some carelessness with regard to quality, but ignorance was a worse evil than neglect. This was particularly true of seamen's food, so regularly the cause of deficiency diseases such as scurvy.

During most of the seventeenth century the theory of nutrition was still that of Galen, governed by the idea of the four 'humours', each considered to be 'hot', 'moist', 'dry', or 'cold' in any of one to four degrees. The humoral theory was itself based on the Aristotelian conception of the four elements, which had declined in esteem but was not yet finally renounced. Walter Harris (1647–1732), with others, tried to substitute for the humoral system a primitive chemical notion of disease (1689), but such scientific thrusts were still widely disregarded, and prejudices remained firm. Milk, for example, was believed suitable only for the very young and the very old. Vegetables were distrusted on the grounds that they engendered wind and melancholy.

Sanctorius (1561–1636) and Van Helmont (? 1577–1644), original as their investigations were, did not cast much more light on the processes of digestion, or on the nutritive needs of the healthy individual. Nor were the next two generations of chemists more successful. The usual method of analysing a foodstuff was to submit it to destructive distillation; the 'watery', 'oily', and 'saline' products obtained were then examined, and many erroneous conclusions drawn. Some chemists thought they could distinguish between 'alkaline' and 'acid' foods, and prescribed their use accordingly. Not till the late eighteenth century were new views on the nature of chemical compounds established, as the result of the investigations of Black (1728–99), Priestley (1733–1804), Scheele (1742–86), and Lavoisier (1743–94). They were hardly applied fully to organic substances before another fifty years had passed. Thus deficiency diseases continued unrecognized as such, misunderstood, and (before about 1750) virtually untreated. The victory over the first of them, scurvy, and the remedy, the drinking of fresh fruit-juice, were purely empirical, owing nothing to chemical science or indeed to the prevailing ideas on dietetics.

Digestion in the stomach was still regarded as akin to putrefaction. Réaumur (1683–1757) made experiments in which a young kite swallowed open tubes full of food, and disgorged them after a short while. Similar experiments were made by Stevins of Edinburgh (1777), who found like Réaumur that food was softened and dissolved in the stomach, and also by Spallanzani (1729–99). Lavoisier finally approached modern theories, holding that the products of digestion are carried to the lungs by the blood-stream and oxidized there.

These few examples show how modern views on diet and nutrition were beginning to dawn at the close of the eighteenth century.

We observe the following factors playing an ever-growing role:

1. The New Husbandry with its scientific and intensive agriculture and co-ordinated system of food-production extends over a large part of the world, and involves the mechanization of the farm.
2. The automatic mill and the mechanization of bread- and flour-making herald the mass-production of other foodstuffs.
3. The new analytical chemistry, applied to the testing of foodstuffs, raises the standard of quality.
4. Chemical and physiological evaluation of food makes the scientific study of nutrition possible.
5. Such new methods of food preservation as canning, desiccation and evaporation, and refrigeration permit the world-wide distribution of food-supplies.

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2

METALLURGY AND ASSAYING

CYRIL STANLEY SMITH AND R. J. FORBES[1]

I. RENAISSANCE WRITERS ON METALLURGY

No spectacular new discoveries or inventions modified metallurgical methods during the sixteenth and seventeenth centuries. This period, however, is important for the large-scale application of metallurgical methods, helped by rising capitalism and mechanization, and is technically significant since it saw the systematization of those methods.

The spread of printing released a stream of metallurgical knowledge codified in carefully prepared treatises. Early in the sixteenth century we have the first modest attempts in the illustrated *Bergwerkbüchlein* ('Essay on Mining') and *Probierbüchlein* ('Essay on Assaying') [1]. Many medieval collections of workshop recipes must have circulated among adepts or pupils in mining and metalworking, from which these first printed manuals descend, and they are certainly reflected in the 'Books of Secrets' (p 33). Traces of them can also be found in J. A. Pantheus's *Voarchadumia contra alchimiam* (1530), a rare work of alchemical interest whose title is explained by the author as 'gold of the two reds' [cementations] [2]. It claims to oppose common alchemy, and contains among other matter a series of strictly practical recipes, probably Latin translations from an Italian workshop recipe-book, concerned with the metallurgy of the more precious metals and materials. Its illustrations of metallurgical processes sometimes have little association with the rather fanciful text of the book (figure 19).

Ten years later (1540) the Italian Vanoccio (or Vanucci) Biringuccio published his *Pirotechnia*, the earliest comprehensive handbook on metallurgy [3]. Its first four chapters deal with smelting the ores of gold, silver, copper, lead, tin, and iron. They contain the first fairly complete description of silver amalgamation, of a reverberatory furnace, and of the liquation process. In its description of mining and smelting Biringuccio's important work is, however, surpassed by that of Georgius Agricola [Georg Bauer], whose *De re metallica* (1556) is one of the great monuments of technology by reason of the comprehensiveness of its text and the detail and intelligibility of its numerous illustrations [4].

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[1] Professor Forbes has supplied the greater part of Sections I to III; Professor Smith the remainder of the chapter.

Agricola (1494–1555) was a physician practising at Joachimsthal in one of the most prolific mining districts of Bohemia, and at Chemnitz in Saxony. He became interested in mining and metallurgy, and after extensive travels set himself the task of recording the knowledge he had gained, achieving a clarity and a conciseness well above those of his contemporaries. Two of his other works are important to the metallurgist in particular. In 1546 he published a volume of four essays: the first is on physical geography (*De ortu et causis subterraneorum*), the second is on sub-surface waters and gases (*De natura eorum quae effluunt e terra*), the third is the first systematic treatise on mineralogy (*De natura fossilium*),[1] and the fourth is a history of mining and metallurgy since antiquity (*De veteribus et novis metallis*), to which was added a glossary of mineralogical terms in Latin and German (*Rerum metallicarum interpretatione*). At the same time (1533–53) he was occupied with his main work, which was published posthumously. For two centuries *De re metallica* remained the chief textbook on mining and metallurgy; its frequent reprints prove the continuity of metallurgical traditions.

The third important author of this period is Lazarus Ercker (d 1593) who also worked in the Erzgebirge between Saxony and Bohemia. His 'Treatise describing the foremost kinds of Metallic Ores and Minerals' (1574) [5] is less concerned with mining and smelting, but by giving more precise instructions on assaying it supplements Agricola's work. The growing knowledge of assaying and evaluating ores and metals formed an important factor in the rise of a quantitative chemistry.

Two more works on metallurgy merit our attention. The first, the *Bericht von Bergwercken* ('News of Mines') by Georg Engelhard Löhneiss (1617) has some valuable discussion of the organization of mining and its employees, but the technical information is largely copied from Ercker [6]. The *Arte de los Metales* of Alvaro Alonzo Barba (1640) is mainly concerned with smelting operations as practised in the gold and silver mines of the New World, and contains few important remarks on European metallurgy [7]. Some information can also be gleaned from Johannes Mathesius's *Sarepta oder Bergpostil*, a collection of sermons to miners and smelters, and the manuscript *Bergbuch* of the Swede Peder Månsson written between 1512 and 1524 [8].

As authorities on metallurgy Biringuccio, Agricola, and Ercker dominate the sixteenth and seventeenth centuries. A new period begins in the eighteenth century with Réaumur's essay on the art of converting iron into steel (1722), and Schlüter's metallurgical handbook (1738) [9]. At about this time, too, the smelting of ores with coke and new methods of producing iron and steel were introduced. The earlier works were mainly concerned with the smelting of gold and silver ores; copper, lead, and tin were treated more superficially and the metallurgy of iron was given little attention. Indeed Réaumur's is the first reliable treatise on iron metallurgy, which is the more strange because this period was one in which the iron industry expanded enormously, with some notable technical advances.

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[1] In medieval and Renaissance Latin *fossilia* signified not fossils but minerals, 'things that are dug up'.

The growing art of assaying and the attempts at classification of the minerals, ores, and metals, though meritorious, were not yet sufficiently precise to permit the identification and exploitation of new metals. They were to bear fruit in the eighteenth century, when many new metals were added to the 'seven' known to the alchemist and metallurgist of our period [10].

II. THE MINOR METALS

The semi-metal arsenic had long been known. Alchemists of the thirteenth and fourteenth centuries referred to it as *arsenicum metallinum*. Pantheus (1530) gives a recipe for a mixture of realgar, orpiment, quicklime, white tartar, and albumen, which when heated in a closed vessel yielded bright silvery arsenic by sublimation, to be used in alloys for mirrors. The first precise description of its preparation is in Johann Schroeder's *Pharmacopoeia medico-chymica* (1641), translated as 'The Compleat Chymical Dispensatory' (1669). Schroeder prepared the element by either decomposing orpiment with lime or smelting arsenious oxide with charcoal.

Metallic antimony produced by smelting stibnite with iron or copper, or by roasting to yield the oxide and reducing this with charcoal, enjoyed a certain vogue in this period because Paracelsus and his followers claimed miraculous effects for its compounds, and even for medicine drunk from a vessel made of antimony.[1] Antimony is discussed at length by the pseudonymous 'Basil Valentine' [Johann Thölde] in his 'Triumphal Chariot of Antimony' (1604). Agricola mentions the smelting process in his *De natura fossilium*, and attaches some value to the metal as a component in type-metal and in pewter.

Bismuth seems to have been known in the fifteenth century, when it was used in type-metal. Paracelsus vaguely mentioned it as a kind of antimony [11]; both Agricola (in his *Bermannus*) and Barba defined it as a metal differing from tin and lead. However, some metallurgists still believed it to be of a composite nature and give recipes for compounding it. Not until the eighteenth century was it fully recognized as a distinct metal.

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[1] Wine placed in an antimony vessel dissolves some of the metal, which is a powerful emetic.

Much the same may be said of zinc. Though produced in India and China during this period [12] and imported from the east by European merchants as 'pewter' or 'spelter'[1] we find only vague and distorted passages in the works of Paracelsus, Cardan, and others referring to the occasional production of metallic zinc in lead-smelting. This 'jagged ore' was often considered a 'semi-metal' (Cardan), an 'imitation of tin and silver' (Agricola), or a 'white or red marcasite of the nature of copper' (Libavius). By the early seventeenth century, however, the metal was being collected from furnaces smelting lead-zinc ores. Henckel isolated it in 1721 and described it in 1743, not knowing that in 1742 Anton von Schwab had distilled it from calamine. A. S. Marggraf smelted zinc from calamine in 1746. Hence, like nickel and cobalt, zinc was recognized merely as a freak product, hardly applied before the end of the eighteenth century.[2] See, however, pp 37, 51.

III. THE IRON INDUSTRY

The main features of sixteenth- and seventeenth-century metallurgy are its mechanization and its spread. The works of Agricola and Biringuccio portray and describe improved mining-shafts, hoists and ventilators, stamp-mills, crushing-, jigging-, sieving- and roasting-apparatus all driven by water-power. Certainly, metallurgy profited much from the introduction of the water-wheel as a prime mover, while the rising capitalism of western Europe found the money to build the large apparatus that the engineers designed. All the big banking firms of those days, such as the Fuggers and the Welsers, were heavily involved in the mining projects of the noble landowners, and thus contributed to the world-wide distribution of metals and metal products. Far more attention was now given to the legal aspects of mining, and the rights and duties of miners and smelters were carefully regulated. The state increasingly intervened in the metal industries which, especially in the manufacture of bronze and iron, contributed powerfully to its warlike potential [13].

During the Middle Ages the price of iron had been fairly stable, though wages and the price of raw materials rose steadily; but with the general rise in prices during the sixteenth century iron rapidly became much dearer. Even with larger blast-furnaces, and with better machines for producing blast-air by means of water-power (frontispiece; plate 3), the effects of the increased cost of labour and fuel could not be wholly overcome. The merit of the blast-furnace was that its iron could be cast, while the wrought iron obtained by working the pigs in

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[1] These two words are cognate but of unknown origin. The name zinc seems to have been invented by Paracelsus.

[2] For the use of zinc compounds in the manufacture of brass, see p 37 and vol II, pp 53-55.

'chaferies' was also of higher quality than that obtained from the older furnaces, owing to proper slagging of the impurities in the ores treated. Its greater efficiency and the higher percentage of iron obtained from a given ore were not in themselves sufficient to balance the quickly rising expenses of the smelting-plants.

The consumption of iron[1] rose steadily with the frequency of wars and the mechanization of armies. The growth of the industry was, however, seriously impeded by the lack of timber, for metallurgy was still dependent upon charcoal. Ironmasters and ship-builders were the great destroyers of forests, and it was often necessary to protect them from the active resentment of the local population. In Britain the rise of the iron industry in the Weald of Kent in the sixteenth century aroused protests against the increased cost of timber, while in the Forest of Dean the use of timber was limited to building and charcoal-burning, coal taking its place as a domestic fuel (p 78).

In these iron-working regions military contracts employed many thousands of men, who in time of peace found an outlet for their cast iron in the form of fire-backs, fire-dogs, pots and boilers, and the like. Armies made away with much cast iron; thus Tilly fired 12 000 to 18 000 cannon-balls into Magdeburg every day during his siege of the town in 1631.

In Britain deforestation was particularly severe, leading to the decline of the iron industry in the Weald and the Forest of Dean. New furnaces were built in south Wales, Shropshire, and the midlands, and a powerful incentive was provided for the discovery of a method of smelting with coal, for which several ineffective patents were taken out in the seventeenth century. In 1720 Britain still produced some 25 000 tons of pig iron and 13 000 tons of bar iron annually, though over 10 000 tons of the latter had to be imported, mostly from Sweden.

A similar increase of iron-production occurred in Sweden, where the blast-furnace was introduced in the later Middle Ages. Sweden, with its rich ores and its wealth of timber, became an important producer of high-quality bar iron and steel. Gustavus Vasa (1523–60) encouraged the building of blast-furnaces, and, to improve the quality of Swedish iron, invited foreigners to assist the young Swedish industry. By 1620 Swedish exports of cast iron cannon already aroused concern in England, which had enjoyed almost a monopoly. In the early eighteenth century two Swedish scientists, Emanuel Swedenborg (1688–1772) and Christopher Polhem (1661–1751), did much to improve Swedish metallurgical and mining methods. As a result, the production of their country rose to 32 600 tons in 1720 and to 51 000 tons in 1739. Similar expansion occurred in other countries, including the British colonies in North America, where there were by 1732 six blast-furnaces and nineteen hammer-forges, besides numerous bloomeries.

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[1] About 60 000 tons in 1500, Germany (30 000 tons) and France (10 000 tons) being the largest producers [14].

This higher production of iron was mainly achieved by using larger furnaces with an increased air-supply. Thus, roughly between 1500 and 1700, the volume of the *Stückofen* (vol II, p 73) rose from 1·1–1·7 cu m to 3·4–4·5 cu m, and the daily output grew from 1200–1300 kg to 1800–2100 kg. Whereas the blast-furnace of 1500 produced perhaps 1200 kg of pig iron a day using double the weight of charcoal, by the eighteenth century the furnaces produced 2000 to 2500 kg a day, and the fuel consumption was greatly reduced. This larger production was attained by adopting a continuous process, in which ore and fuel were fed into the furnace as the pig iron was tapped. In 1600 in the Siegen area of Germany the cycle lasted some 7 to 24 days before the furnace had to be stopped for repair. In the Weald the 'found-day' rose from 6 days in 1450 to 40 weeks in 1700. Hence the large, efficient furnace tended to displace such more primitive forms as bloomeries using batch processes.

Wooden box-bellows invented by Hans Lobsinger of Nuremberg (1550) slowly displaced the older leather ones in the larger furnaces. Mechanization, however, affected mining and the working of iron and steel more than smelting itself. Water-driven hoists for filling blast-furnaces were exceptional; usually men or animals still served. Water-wheels were mainly used in hammer-forges and rolling-mills, and for wire-drawing. Rolling- and slitting-mills developed quickly during this period, though they were not strong enough to produce good sheet iron until 1750. They were mainly used for bar iron, sheet lead, and the like. Originally invented in the Middle Ages for the production of the H-shaped lead ribs for stained-glass windows, they increased rapidly in number in the sixteenth century, spreading to all countries. Power-driven tilt-hammers became common in the sixteenth century, possibly as a result of some Italian improvements, yet the manual hammer retained its position in the lighter branches of the iron industry, such as nail-making, until the nineteenth century.

Most of the iron produced was still wrought iron, though the consumption of cast iron was large, and growing. The fusion of iron, which was rapidly becoming one of the most commonly used metals, so that it could be cast, gave a great impulse to casting techniques. Cast iron could be applied in many ways where stone, wood, or other metals had formerly served, and much wrought iron ware was now made by refining the cast iron pigs. New methods of making steel were investigated, and the number of patents to this end increased notably during the seventeenth century. Anton Zeller of Aschhausen in 1608 proposed to manufacture steel by a cementation process, wrought iron rods being heated with beech-charcoal in 'boxes'. In other processes wrought iron bars were immersed in a bath of molten pig iron, so that their carbon-content was increased and they were converted into steel. Until the structures of iron and steel were better understood such attempts were inevitably inefficient. Lack of proper temperature control was a serious defect in all metallurgical endeavours.

The efficiency and indeed the survival of the iron and steel industry depended on the discovery of a plentiful substitute for charcoal. The cost of fuel was a dominant factor in other types of ore-smelting; these too expanded and spread to many countries without materially changing in character. Certain processes became more popular; thus amalgamation, the extraction of gold and silver from their ores with the aid of mercury, was more commonly used, notably in the New World. The liquation of copper ores with lead provided a most important supply of silver. However, no fundamentally new process was added to the inheritance from the classical world, so well preserved during the Middle Ages. Rapid progress came only in the eighteenth century with new inventions in every field of metallurgy.

IV. UTILIZATION OF IRON AND STEEL

In the sixteenth and seventeenth centuries the craftsman's knowledge was still far in advance of theory, and apart from the few great treatises already mentioned, the writings of purely practical men—mint-masters, locksmiths, jewellers, gunfounders, and the like—give the best insight into the metallurgical equipment and methods of the time. This is especially so for iron and steel, though the new use of cast iron was one of the few real innovations of the period. The literature on the ferrous metals before the sixteenth century is insignificant, and even the Renaissance writers have far less to say of them than of the precious metals, and of copper and its alloys. The recipes in the 'Books of Secrets' [15], and the accounts of Baptista Porta (1589) [16] and Jousse (1627) [17], are somewhat feeble precursors of the first real study of ferrous metals, that of Réaumur (1722) [9].

Here we have to consider the essential differences between the various forms of wrought and cast iron and steel. Before the recognition in the late eighteenth century of the role of carbon the distinction was almost entirely one of furnace operation. Slight modification of iron-smelting processes would produce material with more or less carbon. A shallow fuel bed gave sponge iron. Cast iron resulted from the operation of a high-shaft blast-furnace which would hold the reduced iron in contact with charcoal and produce a high-carbon alloy of low melting-point. Depending on the ore and on the manner of operation a white or grey iron would result, though only the latter would be used for foundry work. Castings were made either direct from the blast-furnace or after remelting.

Saint-Rémy (1697) mentions the casting of iron cannon directly from a blast-furnace in Périgord [18]. The furnaces were 24 ft high and in a single cast yielded enough iron to make an eight-pounder nearly a ton in weight. For larger pieces the products of four blast-furnaces were combined. Musket-balls were cast of iron, though the best, according to Biringuccio, were forged in special dies [3]. Cannon-balls were usually of cast iron, though cast lead and cut stone were not extinct in his day. The moulds were split, cast in either bronze or cast iron, and contained as many as seven cavities. They were dressed with washed wood-ashes and held in specially designed tongs. The furnace was a high built-up forge (essentially a low cupola) arranged for tapping at the bottom. Although the *Feuerwerkbuch* of 1454 had mentioned the addition of antimony, tin, and bismuth, perhaps to improve fluidity, Biringuccio recommends cast iron alone, 'the crude corrupted kind that has been sent through the furnace to purify it of earthiness' [19].

Smiths produced much steel for agricultural tools by direct reduction of the ore in a hearth. A better quality was made either by the carbonization of soft iron or by the decarbonization of cast iron. The production of steel as described by Biringuccio (1540) consisted essentially of dipping blooms of wrought iron sponge into a bath of molten cast iron until sufficient carbonization had taken place, then forging and quenching. Ercker (1574) mentions both carbonization in a charcoal fire and decarbonization by repeated forging [5]. The case-hardening of iron files and other tools is described by Theophilus (vol II, p 63), Biringuccio, and many of the innumerable 'Books of Secrets'. Generally it was a small-scale operation. A single object was plastered with a carbonizing (and often nitriding) compound and protected by an exterior jacket of clay or sometimes of iron. The Neapolitan Giambattista della Porta, in his *Magiae naturalis* ('Natural Magick') (1589), describes the simultaneous hardening of many files or pieces of armour [16]. They were packed in iron chests, interlayered with a compound of chimney soot, glass, and salt or powdered horn. This operation was evidently carried out on a relatively large scale, for provision was made for removing test samples from time to time to check progress.

The complete cementation of bars of wrought iron to give steel for subsequent working into all kinds of objects is first described in detail in Robert Plot's 'Natural History of Staffordshire' (1686) [20]. The process was not very much different from that in use for making blister steel even as late as the present century. The furnace was like a baker's oven with a fire-box 2 ft wide, heating coffers that contained over half a ton of iron in bars up to 5 ft long. Cementation was done with charcoal without admixture, and was continued for between three and seven days and nights.

Though crucible-cast steel did not become important in Europe until Huntsman developed it commercially in 1740, it had been produced in India under the name of *wootz*,[1] and was known to at least two seventeenth-century English writers. Robert Hooke in his diary notes in 1675 that 'steel was made by being calcined or baked with the Dust of charcole, and that bringing it up soe as to melt made the best steel after it has been wrought over againe, that it would be at first porous but upon working and hammering as fine as glasse' [21]. To Joseph Moxon (1677) cast steel was a substance familiar enough to be used for comparison with Damascus steel.

Hardening of Steel. The heat treatment of steel is an ancient art, and the literature of the sixteenth century merely summarizes age-old artisan practice. Though water was no doubt generally used for quenching, the 'Books of Secrets' describe quenching liquors based on vegetable juices, snails, blood, dung, urine, the dew of a May morning, or solutions of inorganic salts. The booklet *Stahel und Eysen kunstilich weych und hart zu machen* (1532) describes the quenching of steel thus: 'Get your iron hot but not too hot. When it is at the correct heat plunge it in the mixture, as far in as is to be hard. And let the heat go out by itself until it takes on little flecks of a gold colour. Then cool it off completely in the water and if it is very blue it is still too soft.' Whatever the nature of the gold flecks, a careful visual control of the quenching temperature is indicated [64].

The best sixteenth-century description of the heat treatment of steel is in Porta's 'Natural Magick' (1589) [16]. He was clearly aware of the possibility of obtaining proper hardness both by direct quenching and by quenching and tempering. He cautions against quenching too hot, and recommends oil quenching to avoid excessive brittleness or warpage. Hardened armour-plate, made by carbonizing in a chest and quenching, is hard and brittle. He recommends a duplex quench for swords, which need softness in the body combined with a sharp edge: the body with an oily, the edge with an acidulated, material. His best description is perhaps that of a tool to cut stone. The English translation (1658) reads:

> The business consisted in these difficulties. If the temper of the Graver was too strong and stubborn, with the vehement blow of the Hammer it flew in pieces: but if it was soft, it bowed, and would not touch the stone: wherefore it was to be most strong and tough,

---

[1] Or *wudz.* Kanarese *ukku,* steel.

> that it might neither yield to the stroke, nor flie asunder. Moreover, the juice or water the Iron must be tempered in, must be cleer and pure: for if it be troubled [turbid], the colours coming from heat could not be discerned: and so the time to plunge the Tools in would not be known, on which the whole Art depends . . . and because that the Iron must be made most hard and tough, therefore the colour must be a middle colour between silver and gold: and when this colour is come, plunge the whole edge of the Tool into the liquor, and after a little time, take it out; and when it appears a Violet-colour, dip it into the liquor again, lest the heat, yet remaining in the Tool, may again spoil the temper.

Clearly an interrupted quench is described. The first colour is that to which the steel is heated for quenching; the second is the temper colour which appears in the actual operation of quenching in the bath, and is not a result of a second distinct operation for tempering. For other purposes he recommends different colours.

The process of quenching directly to give the desired hardness must have called for extreme skill, but when successful would give a tougher product than quenching and tempering to the same hardness. It would be controlled by observing the temper colours formed during quenching, which would necessitate the removal of scale if they were to be correctly observed. Sometimes it would flake off, but Biringuccio and Porta both mention dressing the hot tool with soap to bring out the colours. Probably the efficacy of some of the various organic nostrums lay in the fact that they would modify scaling of the hot steel. Others might cause transitory deposits on the surface of the hot steel and thus delay cooling enough to enable the internal transformation responsible for hardening to occur at the right temperature.

The actual sequence of colours and their relation to hardness is first described accurately by Biringuccio: 'Because the first colour shown by steel when it is quenched while fiery is white, it is called silver; the second which is yellow like gold they call gold; the third which is bluish and purple they call violet; the fourth is ashen gray. You quench them at the proper stage of these colours as you wish them more or less hard in temper' [3].

Mathurin Jousse describes (1627) the sequence of colours on tempering both in the production of decorative finishes and for softening: 'First it will become the colour of gold, then a blood colour, violet, blue and lastly the colour of water. When it has become the colour you wish, you remove it promptly with little tongs' [17]. He is the first writer clearly to prefer quenching, cleaning, and tempering to the ancient process of direct hardening. He checks the temperature for quenching by melting glass, and the tempering of springs just beyond the temper colour range by rubbing a piece of wood against them.

It was natural that Boyle, in his 'Experiments and Considerations touching Colours' (1664), should pay attention to this interesting phenomenon [22]. He lists twenty-five colours appearing in sequence on the skimmed surface of molten lead, and records interesting experiments on hardening small tools. The steel should not be quenched too hot, and should be tempered to the proper colour. He observed that the succeeding colours indicated changes in the 'texture' of the steel, which when tempered yellow was fit for making such tools as axes, and when blue was softer and could be used to make springs.

Robert Hooke developed (1665) a theory of the hardening of steel on the basis of the colours and related it to the hardening of other materials by cold working [23]. He believed that 'the pure parts of Metals are of themselves very *flexible* and *tuff*; that is, will indure bending and hammering, and yet retain their continuity'. The hardening and softening of steel arose, according to him, from varying amounts of vitrified substance interspersed through it, a view remarkably prescient of the amorphous metal theory of nearly three centuries later; but he thought the vitrified substance was derived from 'certain salts, with which [iron] is kept a certain time in the fire' to convert it into steel.

V. COPPER ALLOYS

Brass, made from copper by a kind of cementation process with calamine and charcoal, has been known and used extensively since Greek times (vol II, p 53), though metallic zinc was almost unknown until the sixteenth century. Savot first reported (1627) that zinc alloyed with copper produced brass [61]. Glauber (1656) studied the alloys in more detail, and they found some use for decorative trifles under the name of 'Prince Rupert's metal' [24]. The process of direct alloying from the metals did not displace cementation until well into the nineteenth century.

Biringuccio (1540) has a good account of the furnaces and processes used in making brass. Ercker (1574) described German practice in brass-founding and casting brass plates for subsequent working. English practice is given best by Merrett (1662) [25]. The brass-makers used a special furnace consisting of a deep conical hole below the working floor. At its bottom was a shallow fire containing eight or ten relatively small crucibles filled with a mixture of roasted and ground calamine mixed with powdered charcoal and copper scrap (figure 15). The time of heating varied from 9 to 18 or 20 hours. The excess of weight of the brass over the copper from which it was made corresponds to a resulting alloy with from 29 per cent zinc (Ercker) to 40 per cent (Merrett).

Bronze (vol I, pp 589 ff and vol II, pp 48 ff) is the oldest of all widely used alloys, but its metallurgy is interesting here for the wealth of technological detail available from the sixteenth century. The alloy for general foundry purposes was copper with from 8 to 20 per cent of tin, according to the use in view. For guns and large statues, additions were made of about 1 per cent of zinc in the form of brass. This improved the casting properties. Small household objects generally contained lead, usually about 7 per cent but sometimes as high as 30 per cent. Bell-metal contained 20 to 25 per cent tin, and speculum-metal about 25 per cent, often with addition of arsenic and silver.

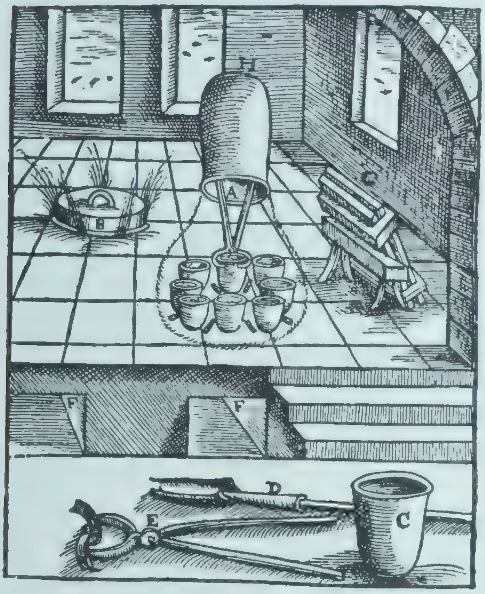

FIGURE 15—*Brass-foundry.* (A) *Interior of furnace [dotted line] showing arrangement of crucibles within;* (B) *furnace in operation;* (C) *crucible;* (D) *scoop;* (E) *tongs for handling crucibles;* (F) *draught-holes for furnace;* G, *stone slab mould. 1580.*

Biringuccio remarked that on adding more tin to copper the metal changes: 'From red which is the colour of copper it becomes white; from soft and flexible it becomes hard and brittle as glass. This admixture removes copper so far from its original nature that one who does not know that it is a compound material believes it to be one of the metals engendered by nature.' The composition must be adjusted to the specific use: 8 to 12 lb tin per hundred of copper for guns, 23 to 26 for bells (depending on the tone). As a brittle material for explosive bombs he suggests three parts of brass to one of tin.

For casting guns Biringuccio emphasizes the importance of a large feeding-head to prevent porosity in the casting, owing to shrinkage, while to avoid what is now known as inverse segregation he added tin to the last metal to run into the mould.

Before the eighteenth century guns were cast with cores, and the boring-mill was used only for trueing the bore (ch 14). All the old writers mention the use of heavy iron chaplets to centre the core at the bottom of the mould (p 365), although surviving guns of the seventeenth century and later rarely have iron embedded in the appropriate places. Though most of the many writers on artillery say little about the cast iron or bronze alloys used for gun-making, Saint-Rémy (1697) notes that the best metal was that made from 87 per cent copper, 8 per cent tin, and 5 per cent brass, but that some founders used a higher proportion of tin (figure 16) [18]. Some founders, he reports, always added at least a quarter of new metal on re-melting old. Others used a potent flux containing saltpetre, antimony, and other materials moistened with nitric acid and plunged beneath the surface of the bronze in a box; this was supposed to free the metal from blowholes, and would probably have been effective through its oxidizing effect. Foundrymen and fluxes have always been inseparable.

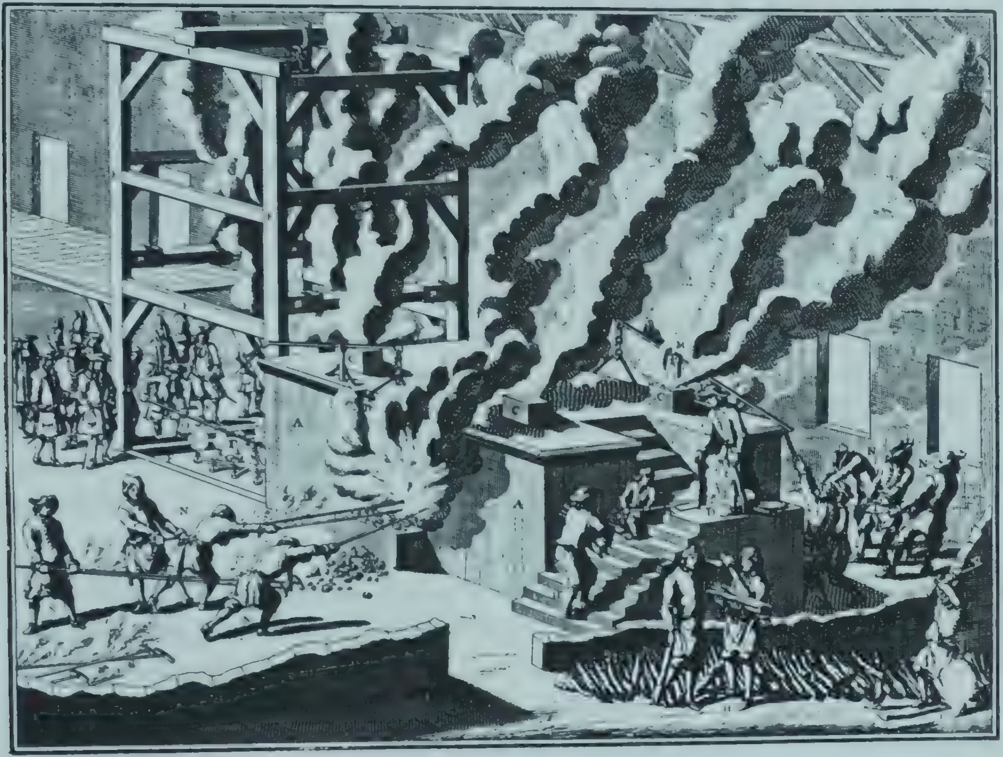

FIGURE 16—*Bronze gun-foundry in operation, 1697. Reverberatory furnaces like these commonly held about 30 tons of metal, which was melted in 24 to 30 hours.*

Some techniques of casting are described elsewhere. Large castings such as guns, bells (figure 17), and statues were made in loam moulds (p 364); small ones from patterns in boxes, much as today's sand-castings are, but with some finely divided refractory material (bone-ash, tripoli, emery, iron oxide, pumice, or brick dust) bonded together with a salt solution or an organic substance, such as egg-white. The making of medallions and other fine-art castings is well described by Biringuccio and also in the 'Books of Secrets', particularly the pseudonymous 'Secrets of Alexis' [15]. The casting of metal in greensand moulds was unusual in the sixteenth century, though it is mentioned by both Leonardo da Vinci and Biringuccio. At the brass-foundry in Milan described by Biringuccio, mass-production of small objects—as many as 1200 in a single mould—was achieved by stacking together sections of dried loam moulds.

Speculum-metal. The outstanding metallic property of reflection had been used since antiquity in both solid metallic mirrors and as a backing to glass. Månsson describes (*c* 1515) the application of tin to glass with mercury, while Hans Sachs mentions (perhaps with poetic licence) lead (1568), and Biringuccio antimony (1540), as a backing for glass [8, 26, 3]. Porta refers to tin amalgam on glass (1589), and also to a kind of Christmas-tree ornament lined with an alloy of antimony and lead by pouring in the molten metal and draining out that which did not stick [16]. Most mirrors, however, were from antiquity made solid of speculum-metal. Pliny, for example, mentions the use of two parts of brass to one of tin. Biringuccio refers to the 'old' composition of three copper, one tin (sometimes with one eighteenth of antimony or one twenty-fourth of silver), but prefers to use an alloy of three parts of tin to one of copper, with some arsenic added. Though he usually describes casting and polishing from first-hand knowledge, this composition rich in tin would be expensive, brittle, and hard to cast and polish. Leonardo da Vinci, Pantheus, and Porta all give a more normal composition. Porta recommends adjusting the composition of the melt on the basis of the appearance of the fracture of a sample of the metal taken on an iron rod.

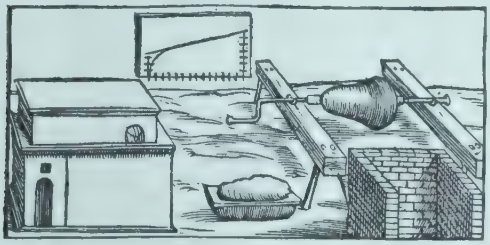

FIGURE 17—*Bell-founding, 1540. The size and shape of the bell to be cast were proportioned to the thickness of the rim, which was taken from a traditional scale according to the weight of the bell desired. From a drawing made according to the rules strickle-boards were cut, with which to shape the moulding-clay to the form of the core and the outer mould. The core was formed first on a spindle; then on this, covered with ashes, more clay was built up to the exterior dimensions of the bell, with inscriptions or ornamentation added in wax. This 'case' was coated well with tallow, to receive the outer mould. After thorough firing the outer mould was lifted off, the 'case' was cut away from the core, and then the two parts of the mould were fitted together, now with a space between them which was to be filled with bronze.*

Glauber (1651) gives the best description of both the casting procedure and of the metal itself [27]. He points out that the harder the metal the better it is for polish, though whiteness is needed also: 'Red comes from too much copper; black from too much iron, or dusky from too much tin.' His composition was essentially a copper-tin-arsenic alloy. Copper plates were packed in white arsenic impregnated with linseed-oil and heated so that the arsenic could diffuse into the plate, like 'oil piercing dry leather', thereby increasing the thickness of the copper two to three times and making it brittle. Two parts of brass were then melted in a quick fire, one part of the arsenic-copper was added, and the alloy was cast into an ingot, which was re-melted with one-third of its weight of the best tin and cast into specula. The alloy could also be made directly by melting three parts of copper, one of tin, and one-half part of white arsenic.

Neri (p 217), a reliable writer on glass, mentions (1612) a composition like Biringuccio's which, when melted, is treated with a flux of tartar, saltpetre, alum, and arsenic [25]. J. H. Cardalucius, in his notes to Ercker (1672), recommends equal parts of copper and tin to which, when molten, are added one part of arsenic, one-half part of antimony, and one-half part of tartar. Since there was no control of mechanical properties in the resulting product, the alloy was ripe for experimentation. Merrett, in his English translation (1662) of Neri, mentions additions of antimony, bismuth, mercury, silver, and zinc.

The Royal Society records a letter (1672) from Isaac Newton, inventor of the reflecting telescope, in which he remarked that speculum-metal often contained small pores, visible only under the microscope, which wear away faster than the rest of the metal during polishing and thus spoil the image. He comments that bismuth mixed with bell-metal makes it white, but its fumes fill the metal full of microscopical pores 'like so many aerial bubbles', while arsenic both whitens and solidifies the metal [28]. Later the Society experimented with steel mirrors, and also received a proposal from Hooke to make reflecting telescopes in great numbers by stamping plates of silver in the screw-press at the Mint between concave and convex dies [29]. Silver had been mentioned as a material for unbreakable mirrors by Pantheus (1530) [2].

Bearing-metals were of surprisingly little concern to writers on metallurgy and engineering earlier than the nineteenth century, though there are many impressive illustrations from the sixteenth and seventeenth centuries of machines that would not operate successfully without fairly good bearings. Nevertheless, they frequently show what appear to be iron shafts running directly on wooden frames, though often with (apparently) a wrought iron plate protecting the wood. A roller, or rather pulley-like, bearing is sketched by Leonardo and Agricola. The latter mentions bronze for cams in the machine for breaking up cakes of copper. Biringuccio (1540) refers to glass or gun-metal grooves for pendent bells as an alternative to iron-on-steel bearings. Zonca (1607) seems to be the first to remark that, when running against steel, any sort of metal other than brass is consumed; he illustrates separate bearing-blocks in his little mill for rolling lead strips for windows [30].

The best seventeenth-century treatment of bearings is by Robert Hooke, who observes, in reporting to the Royal Society on Stevin's 'sailing chariot', that

> The less rubbing there be of the Axle, the better for this Effect: upon which account Steel Axes and Bell-Metal Sockets, are much better than Wood, clamped or shod with Iron; and Gudgeons of hardened Steel, running in Bell-Metal Sockets yet much better, if there be provision made to keep out Dust and Dirt, and constantly to supply and feed

them with Oil to keep them from eating one another: but the best way of all is, to make the Gudgeons run on large Truckles, which wholly prevent gnawing, rubbing and fretting [31].

Other copper alloys. Arsenic and copper have been closely associated through most of the history of metallurgy. In both the Near East and South America the earliest alloys were of copper and arsenic, soon to be displaced by mixtures of copper and tin. In the sixteenth and seventeenth centuries arsenic was frequently added to other copper alloys to improve castability and colour, but it is mentioned more frequently in the 'Books of Secrets' than in the reputable metallurgical works. 'With arsenic', says Biringuccio, 'fraudulent alchemists blanch copper, brass and even lead to the whiteness of silver.'

Copper alloys containing sulphur, oxygen, and generally iron were inevitably produced during the processes of refining the metal. The copper-lead alloy produced during the desilvering of copper by liquation is of interest in connexion with alloy constitution, for the process depended on the fact that copper and lead are completely miscible in the liquid state at high temperatures, while a molten phase rich in lead and a solid phase rich in copper coexist at a low red heat. Silver is almost entirely concentrated in the lead phase, which can be drained from the interstices of the copper dendrites, carrying with it most of the silver. About 80 per cent of both the lead and silver in the initial cakes could be recovered. This process, developed in Saxony about 1450, deeply affected European economy.

VI. TIN ALLOYS

Tin and alloys rich in tin were used for plating copper and iron, and as solders, while the alloy pewter found many applications. Most old sources agree that the best solder consists of two parts of tin to one of lead, though one-to-one mixtures were most often employed because of their lower cost; five-to-one alloys were used for soldering window-leads.

The name pewter has covered a wide variety of tin alloys at various times and places, and the high cost of tin has encouraged fraudulent adulteration. The best pewter was commonly regarded as that with the highest tin-content, hardened with small amounts of copper, bismuth, and, later, of antimony. Cheaper alloys containing lead were used for large or common objects.

The records of the ancient Pewterers' Company contain a draft ordinance of 1348 which indicates that the chief metals used in the craft were brass, tin, and lead. The Company appointed overseers to supervise the alloys and the work of the pewterers. They were empowered to assay for the detection of fraud. The best pewter vessels should have 'the measure of brass to the tin as much as it would receive of his nature of the same; and all other things of the said craft that be wrought, as pots round that pertain to the craft, to be wrought of tin with an alloy of lead to a reasonable measure; and the measure of the alloy of a hundred tin is 26 pounds lead' [32].

Bismuth as an addition to pewter was mentioned by Bishop Roderick in 1471, but its first appearance in the English records (under the name of 'tinglass') was in 1561, when a member was disenfranchised for revealing the secret of its use. By 1619 2½ lb of bismuth were added to every thousand of tin. Later, this weight was increased to 3 lb, with a rider allowing more or less as the tin would bear it. Harrison (1577) [33] gives the composition of English pewter as 30 lb of brass to a thousand of tin and 3 to 4 lb of bismuth, while Houghton (1697) [34] says that the copper varies between 3 to 6 lb per hundred of tin, depending on the fineness of the tin, while a few ounces of zinc are added to improve the colour.

The pewterers' casting process was very simple and usually involved permanent moulds of soft stone or metal. Sand- or composition-moulds were used for complicated objects. The tin-rich alloy for plates and high-quality ware was generally hammered to improve its solidity and finish, while the cheaper alloy ('lay') was cast directly into the shape of the desired vessels, which were dressed and used with no further treatment. Continental pewter was similar.

There are many early references to alloying for the purpose of improving the sound of the metal. On the European continent material known in the seventeenth century as *étain sonnant* or *stannum sonans* was composed of 100 lb of tin with 1 or 2 lb of copper and 1 lb of bismuth, contrasting with common pewter of 12 to 15 lb of lead per hundred. The fact that the common adulterant of tin was lead permitted the use of density as a relatively easy method of assay (p 68).

The first mention of antimony for hardening tin is by Biringuccio, but its use did not become common until late in the eighteenth century. Alexis (1555) adds an eighth part of antimony 'to harden it and make it sound well' [15]. Glauber gives more detail [24]. One part of antimony to twenty of tin gives a hard enough alloy, while with less than twelve parts of tin the alloy is brittle and useless. Tin may, he says, also be alloyed with zinc instead of antimony; indeed, it is then easier to melt.

Type-metal. There seems to have been a close connexion between the pewterer's art and the invention of printing. Although, by the seventeenth century, lead-based alloys were being used for casting type, sixteenth-century descriptions imply tin-base alloys. Thus Plantin (1567) says loosely 'tin or lead', while Hans Sachs in his jingle appended to Amman's famed woodcut (1568) (figure 254) says, 'bismuth, tin and lead' [35, 26]. E. O. von Lippmann (1930) believed that bismuth-rich alloys may have played a crucial role in the invention of type-casting, though to the present author it seems that the ordinary pewterers' compositions with only minor bismuth-content would have met all the requirements for the first trials [11].

Biringuccio gives the first description of type-casting, and the best until that of Moxon in 1683 [3, 36]. He states that 'letters for printing books are made of a composition of three parts of fine tin, an eighth part of black lead, and another eighth part of fused marcasite of antimony'. This corresponds to 92·3 per cent tin and 3·85 per cent each of lead and antimony—a tin-rich composition of a kind that would be familiar to a pewterer. When one considers also the close similarity between the type-caster's mould, with its adjustable permanent parts and replaceable matrix, and the pewterer's stone or metal moulds, often with undercut or relief parts arranged to be withdrawn separately, it seems probable that Gutenberg was strongly influenced by the pewterer's art. His genius lay in combining and adapting existing techniques, for he did not need to originate in detail all the many devices and procedures that made printing possible. Movable type could have been laboriously cut by hand or cast from patterns in moulds of sand or clay, as indeed the Chinese seem to have done, but the critical part of Gutenberg's invention was the realization that the pewterer's material and moulds made possible the cheap production of innumerable identical objects that were accurately shaped, sized, and finished (ch 15).

Two centuries later—and probably much earlier—the initial tin-base alloys had been entirely displaced by the harder and cheaper lead-antimony alloys. A lead-antimony alloy like modern type-metal is described by Moxon [36]. He made it by fusing 3 lb of antimony sulphide with an equal weight of iron and alloying the resulting regulus with 25 lb of lead. This would have resulted in an alloy with 7·9 per cent antimony. Moxon mentions the addition of a little block tin to this to render it more fluid for small letters, and Glauber (1656) refers to a silver-bearing antimony used by type-casters to give fluidity [24].

VII. USES OF LEAD

Lead was extensively used in the commercially pure form for building purposes. For general decorative work it was cast in moulds of stone, metal, or clay, and was often gilded. For reinforcing stained-glass windows, pieces of an H section were made, at first by casting [37] and later by rolling [26, 30, 17]. Before the seventeenth century, sheet metal for roofing was made, as described by Biringuccio, by pouring molten metal down an inclined board covered with a flat bed of sand (figure 18). This was replaced by a horizontal mould only when thick castings were needed for the rolling-mill. De Caus mentions (1615) a flimsy hand-operated rolling-mill for making the cast plates uniform in thickness [38]. Later in the century heavier mills driven by water-power or horse-power were in operation in England. By 1691 'milled' lead sheets up to $3\frac{1}{2}$ ft wide were available in thicknesses corresponding to weights of 1 lb, or up to 20 or more, per square foot [39]. Rolled lead rapidly replaced cast sheets because of its cheapness and freedom from defects. Its use for sheathing boats in 1670 brought about a mysterious disappearance of the wrought iron rudder-fixtures. This wonderful example of electrolytic corrosion resulted in acrimonious debate between producer and consumer, but unfortunately did not lead to scientific investigation.

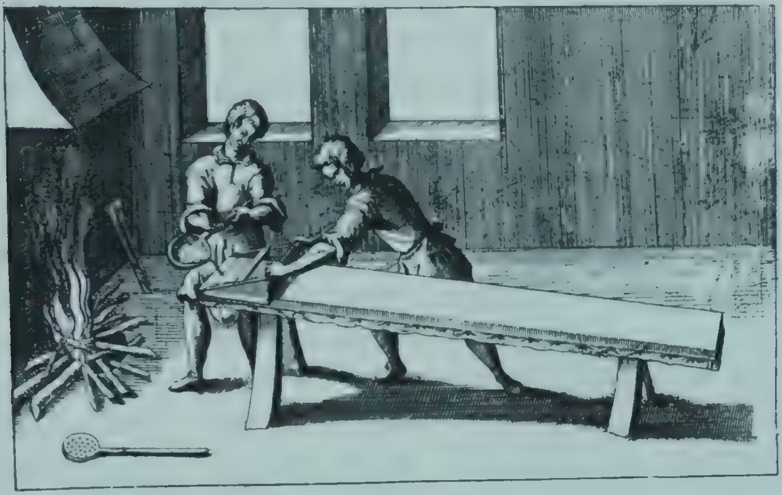

FIGURE 18—*Pouring molten lead or tin upon an inclined sand-bed to form cast sheets of metal. 1624.*

Lead shot was made by casting into a split mould or, after Prince Rupert's invention (*c* 1650), by alloying lead with arsenic and pouring the molten alloy through a kind of colander into a tub of water. Hooke describes the process in detail and comments that the skin formed when arsenic is present contracts everywhere equally and gives a spherical shape [23]. Larger bullets, of course, had to be made in split moulds.

VIII. PRECIOUS METAL ALLOYS AND WORKING-TECHNIQUES

The alloys for coinage and jewelry are of more interest for the techniques used in shaping them than for the alloys themselves, which have remained almost unchanged for millennia. The principal European coins of the fifteenth and sixteenth centuries are all of the ternary system gold-silver-copper. The actual composition changed with the relative value of the metals and the honesty of the governments. Gold coins were sometimes made of the pure metal despite its softness. Up to the time of Henry VIII, English coinage contained only 0·54 per cent of alloy, which was allowed to pay the coiner and for a necessary working tolerance [40]. The Italian ducats and Hungarian florins were also nominally pure gold. Even Henry VIII debased English gold only to 20 carats.[1] The crown of the Holy Roman Emperor was 22½ carats. An initial tolerance as to the nature of the alloying metal was replaced by a general requirement that it be silver and copper in the ratio of two to one. The assayer needed to be alert for the various compositions, and his touch-needles (vol II, p 45) were usually made in three series.

Silver coinage has never been made with the pure metal. It was debased partly for fiscal reasons and partly to facilitate the making of small-value coins of sufficient size. On the continent extensive use was made of *billon*, an alloy containing 20 per cent or less of silver, while in England the lowest was 25 per cent silver, in Edward VI's reign. Elizabeth I restored 'sterling', 925 parts of silver per thousand, which had been and was to remain the standard for English coins for many centuries. The debased coinage that Elizabeth recalled from circulation must have been highly adulterated, for not only was the dross bulky enough to use as road-filling, but many workmen died from the fumes emitted during re-melting. The re-establishment of fine coinage was unpopular, for it left no minor medium of exchange except private merchants' tokens made of lead, tin, or copper, and involved a form of deflation. Though Irish coins of brass and copper were made as early as 1461, it was not until 1613 that royal coins were actually made of copper.

The Commonwealth under Cromwell issued a variety of coins of copper, of pewter with a centre of copper, and even of concentric rings of copper and brass around a central silver disk. Tin coinage (to which the Mint had objected as being too easy to counterfeit with zinc, arsenic, or antimony) was issued in 1684 with a round slug of copper in the centre. Copper was the preferred metal for coins of small value because of the relative certainty of its composition. It was tested by being hammered flat when red hot, for most impure copper alloys will not withstand this treatment.

Metallurgically interesting is the process of blanching, which has been used by both legal and illegal coiners since classical antiquity, to give a fine silver-rich surface to relatively base alloys. Oxidation of such alloys produces a layer of nearly pure copper oxide with the equivalent silver-content concentrated in the surface of the residual metal beneath the layer of oxide. The coins (generally after striking) were annealed in a pan filled with burning charcoal and tossed frequently about so that they would heat uniformly. Pickling, to remove the layer of oxide and so reveal the silvery surface, was usually done in a boiling solution of a mixture of tartar, common salt, and sometimes rock alum. Blanching was part of the standard operations on silver coinage on the continent, and is so described by most writers from the time of the *Probierbüchlein* (pp 27, 59).

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[1] A *carat* is a twenty-fourth part, so that 20 carats means that 4 parts in 24 are not gold. The word *carat* is of Arabic origin (*qīrāṭ*) and in that language meant a weight of 4 grains.

Gold coins seem never to have been given a superficial enrichment, although the process of cementation was a standard one for producing pure gold from gold-silver alloys (vol II, ch 2), and various pickling processes have been used by goldsmiths to give an enhanced colour.

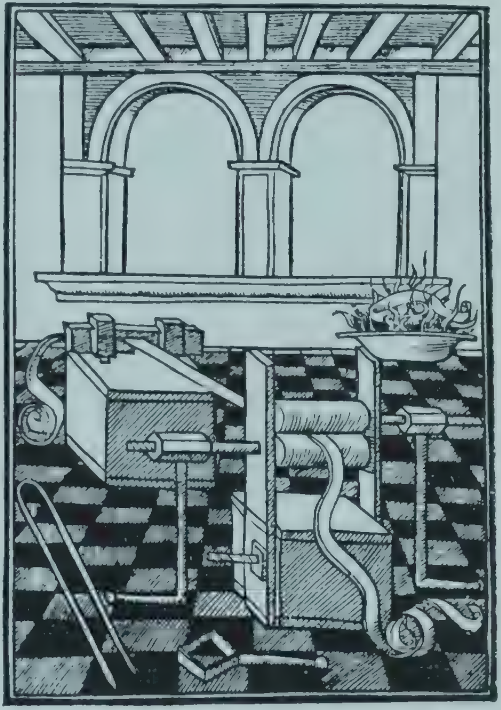

FIGURE 19—(Foreground) *Rolling-mill turned by cranks;* (background) *draw-plate for forming rectangular bars. The artist has mistakenly combined two distinct processes. 1550.*

Though a fair idea of the metallurgical aspects of minting may be derived from Biringuccio and other sources, the *Traité de Monoyes* of Jean Boizard (1696) gives the most detail [41]. In the Paris mint at that time clay crucibles were used holding $42\frac{1}{2}$ lb of gold, while silver was melted in iron crucibles holding up to 650 lb. In the latter the bath was held while a sample was assayed and the composition adjusted before casting. Metallic moulds, dressed with a greasy mixture, had been known to Biringuccio, but the Paris mint was still using the more laborious method of making sand-moulds. The plates were subsequently rolled, but only lightly for adjustment and not for really heavy reductions. Both Leonardo da Vinci and Biringuccio mention a draw-plate with a rectangular orifice, the bar being drawn through with a little windlass. Pantheus (1550) shows a rolling-mill which, despite the seemingly impossible manner of use, is the first realistic figure of the device (figure 19).

The techniques of the goldsmith were so well developed in the Middle Ages that little change has occurred subsequently (vol II, ch 2). The sixteenth-century goldsmith had practical acquaintance with almost all of the problems that interest the twentieth-century scientific metallurgist: change of melting-point and properties by alloying, effects of cold working and annealing, diffusion, surface tension, phase-transformations, and the effects of oxidation and corrosion.

The various solders used for gold and silver, as well as brazing-solder and soft solder, were all essentially of the same composition as at present, and had been described centuries earlier. Amalgams were sometimes used as cold solders. Copper was used as a solder for gold, depending on local alloying to give a low melting-point alloy. The most elegant form of this process, well described by Cellini (1568), was to apply finely ground copper carbonate mixed with a flux [42]. The carbonate was reduced by the charcoal flame used for heating, and locally produced a low melting-point alloy that was carried by surface tension into the crevices to be joined.

For gilding, an amalgam of gold was applied to the object. Wire and plate of silver covered with gold and of copper coated with silver (later to be known as Sheffield plate) were made by preparing a composite ingot before working down. Spun gold (a yellow linen thread covered with metal) was always made with very fine gilded silver tape. Biringuccio made a soldered bi-metal plate with a ducat of gold for every pound of silver; it was hammered repeatedly in the manner of the goldbeater until almost as thin as gold-leaf, when it was cut into narrow strips and applied to the thread. In Boizard's day (1696) the same material was made by flattening a drawn gilded wire between two highly polished steel rolls. The rod for drawing was made merely by cleaning the surface of the silver and rubbing on gold leaves without solder.

The goldsmith made wide use of niello, a low melting-point, black sulphide used as a kind of enamel to fill in incised designs. It was known in Roman times (vol II, p 480) and was described by Theophilus [37]. Pantheus, like Biringuccio a decade later, makes the material by pouring a molten alloy of silver, copper, and lead in the ratio of 1:2:3 into a clay pot filled with powdered sulphur. The contents are then washed and ground to a coarse powder and mixed with a little sal ammoniac, pressed into the incised design on the silver to be decorated, and fused [2, 3]. Though the metallurgist was very familiar with sulphides in refining and parting processes, the jeweller never seems to have made his niello by direct mixture of the sulphides.

The prodigious extensibility of gold has attracted the attention of both philosophers and experimenters. This remarkable property permits the permanent beauty of gold to be widely utilized despite its high cost. The use of layers of metal, paper, or gold-beater's skin to protect the gold during extension is very ancient, and the process as described by Boizard is practically identical with modern goldbeaters' practice. He states that the goldbeaters first forged the gold to leaves of the thinness of paper. These were cut into pieces about 1 inch square, and hammered in 'books' of vellum or of cow-intestine, using three different sizes of hammers in the process of reduction. The finished leaves weighed as little as nine or ten grains for 4-inch-square leaves (125 to 150 sq ft per oz).[1]

For many uses gold-leaf was in direct competition with the powdered metal applied as paint or ink. Theophilus and many of the 'Books of Secrets' describe the wet grinding of gold, silver, and even brass and tin for this purpose. Coloured 'bronze' powder was made by oxidation of copper-alloy filings to give appropriate temper colours.

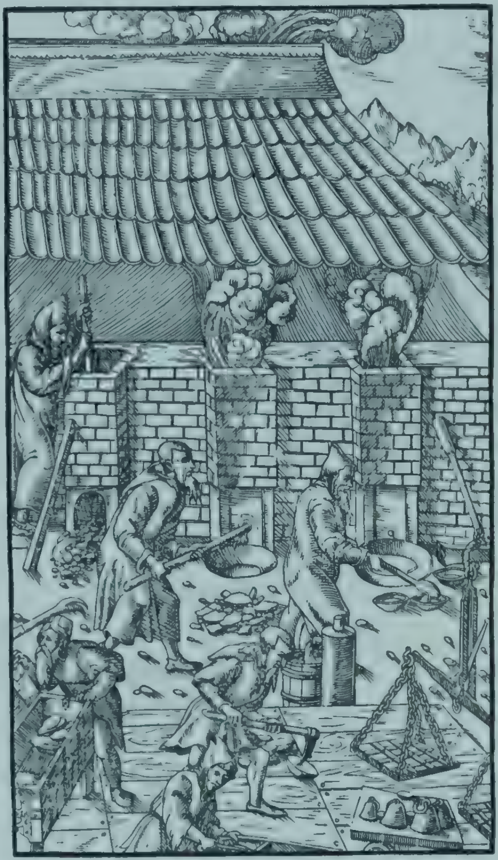

FIGURE 20—*Blast-furnaces for smelting non-ferrous metals. 1556.*

The temper colours produced on alloys by oxidation were used in another decorative application—that of foils placed under gems to enhance their beauty. Biringuccio implies that the foils were a recent development in his day, while Cellini and particularly Porta describe them in great detail [3, 42, 16]. The alloys were of various copper-silver-gold compositions, hammered to thin foils and burnished, then exposed to the heat of a moderate and clear fire to develop the colour. Porta built a special little sheet iron furnace for the process, and sometimes laid goose-feathers or bay-leaves on the coals to obtain special colours.

IX. METALLURGICAL FURNACES

Furnaces can be roughly classified into those for the reduction of ores and those for re-melting the subsequent metal for alloying and casting. Roasting of the ores to remove impurities before smelting was done in open piles, in stalls, or sometimes in reverberatory or open-shaft furnaces, occasionally so arranged that a stream of water could be directed upon the hot ore to quench it, in order to facilitate subsequent crushing. Non-ferrous metals were smelted principally in blast-furnaces of the type described in vol II, ch 2. Sixteenth-century writers such as Biringuccio (1540), Agricola (1556), and Ercker (1574) agree in showing these furnaces built close against a heavy wall separating the furnace-room from the bellows, there being as many as five or six furnaces in a row. The furnaces were rarely more than 5 to 6 ft high, for they were charged directly from the floor. The inside profile was usually rectangular, with sides of about 18 to 24 in and tapering uniformly from top to bottom, although quite complicated profiles were sometimes used, such as the wide middle or double hopper depicted by Biringuccio. The construction of these furnaces is seen in figure 20, from Agricola, and figure 21, from the Marchese della Fratta et Montalbano (1678) [65]. The latter figure shows on the left an unusually high furnace, probably for iron-smelting, with the tuyère (from a *trompe*) inserted in the front. Furnaces for smelting iron were larger than their non-ferrous counterparts. As the utility of cast iron, both for simple castings and as an intermediate step in the production of wrought iron, began to be appreciated between the fourteenth and seventeenth centuries, open hearths (bloomeries) for direct reduction of iron were gradually, though not completely, replaced by blast-furnaces. Furnaces 12 to 16 ft high and 4½ ft wide internally were common by the mid-sixteenth century, and this size had been doubled by the end of the seventeenth (frontispiece; plate 3).

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[1] Mersenne (1621) reports 104 sq ft per oz; Réaumur (1713) 146 [43].

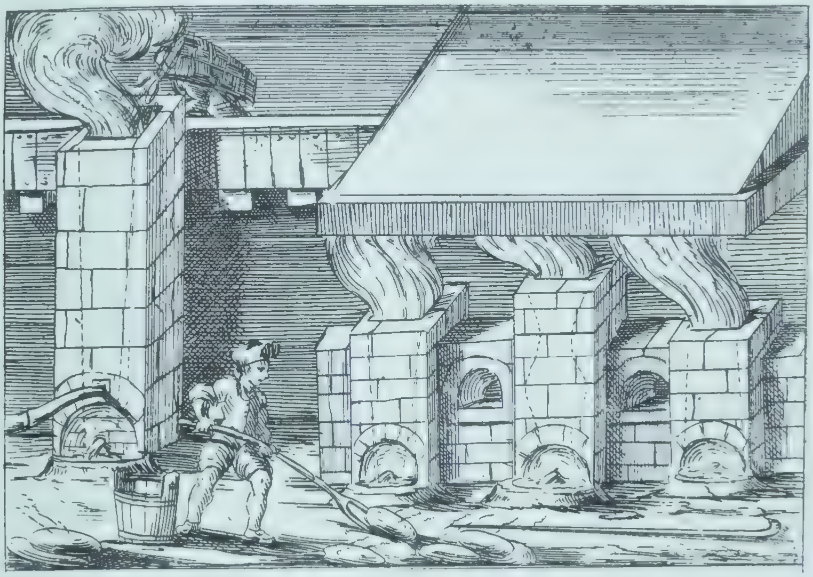

FIGURE 21—*Italian smelting-furnaces. 1678.*

The furnaces were usually built of soft refractory stone with a renewable lining of clay. The crucible was commonly lined with a brasque, that is, a paste of charcoal tempered with clay. Though the iron furnaces were tapped at infrequent intervals, the smaller furnaces for non-ferrous metals were often operated with the tap-hole open, the forehearth (lined with brasque) being depended on to separate slag and metal. Figure 22 shows furnaces for smelting roasted matte to copper and alloying the latter in the forehearth with lead from a little auxiliary furnace to give liquation-cakes. The liquation-hearth itself, to the right of the drawing, had changed very little from the design of a century earlier. This illustration also shows the dust-catching chamber above the furnaces. The deposit collected here, principally zinc oxide, was used in making brass.

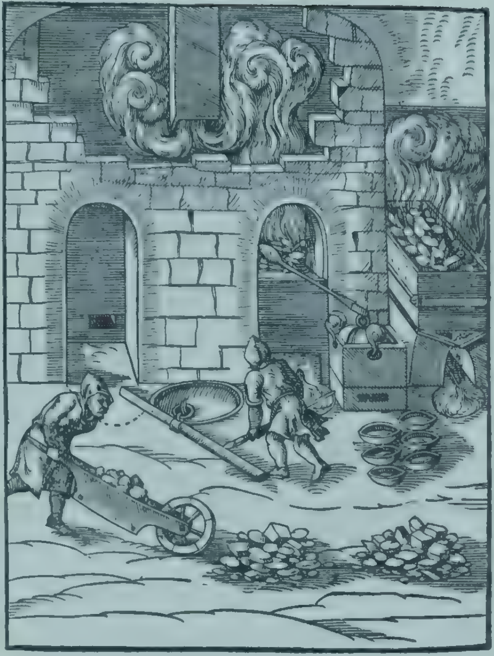

Figure 22—*Furnaces for reducing copper and alloying it with lead to make liquation-cakes in the forehearth. 1574.*

The smelting of antimony and bismuth involved little more than melting the metal or mineral away from the gangue, and was done in small pots or even in open fires, as is well illustrated by Agricola. Mercury was distilled from its ores in inverted pots or in simple ceramic stills. The European smelting of zinc is first described by Löhneiss (1617), who refers to it as an accidental condensate in chinks and cracks of furnaces smelting the Goslar lead ores. By 1700 the fronts of the furnaces were made thin and were intentionally cooled to increase the yield, while in 1734 Swedenborg described a special internal stone slab which, inserted as a false front in the furnace, served as a simple condenser for the metal.

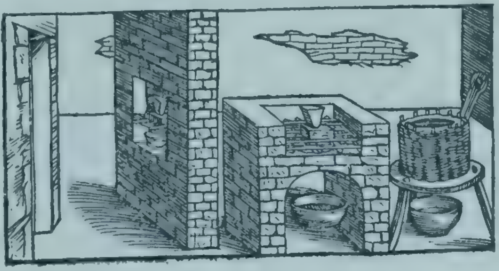

Figure 23—*Wind-furnace for melting metal in crucibles by natural draught. 1540.*

Melting-furnaces were far more diverse in form. Furnaces for melting alloys, either for purification or for casting, were relatively simple (figures 23, 24). The most generally adaptable was the smith's forge worked with bellows. With a few

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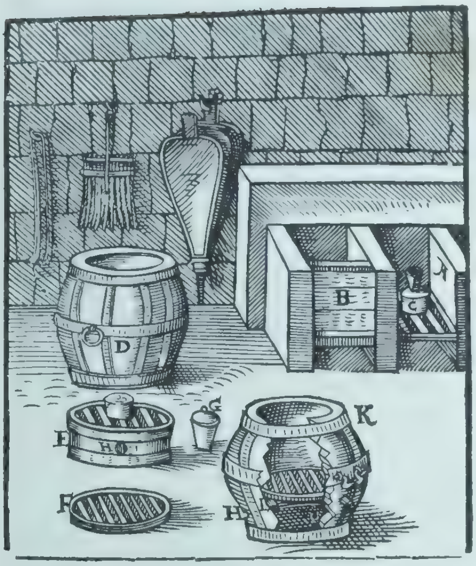

FIGURE 24—*Wind- and blast-furnaces for melting metal in crucibles.* (A) *Interior view of brick furnace with crucible standing on grate;* (B) *the same closed;* (C) *crucible;* (D, K) *furnaces of potter's clay. 1574.*

bricks to hold the crucible in place, this would suffice for almost any metal. Next came the wind-furnace depending on natural draught, though usually only that produced by the height of the furnace itself. Relatively tall furnaces were used by the brass-makers. Although hoods and chimneys for smoke-removal were common, the intentional use of a chimney-stack to enhance the draught is not seen until 1648. In that year Glauber illustrated in his 'New Philosophical Furnaces' [27] a wind-furnace with a properly applied chimney-stack. This had a great influence upon subsequent design (vol II, figure 675).

For melting somewhat larger amounts than could be contained in a crucible, ladles were used. These were lined with refractory clay, which was also built up around the top to hold fuel; combustion was urged by blast from the bellows (figure 25). When the metal was ready for casting, the fuel was raked off and the ladle carried to the mould. Still larger amounts of metal were melted in stationary hemispherical hearths in which metal and fuel were piled together. These were actuated by bellows and arranged for bottom-pouring through a tap-hole and channel, either directly into a mould or into a ladle (figure 26). This kind of furnace could be made of almost any size and became a kind of semi-permanent low-shaft cupola.

Bellows were extremely important to the metallurgist. Both Biringuccio and Agricola devote much attention to their construction and operation. The aeolipile—a kind of steam injector pump—was used with small laboratory blast-furnaces (figure 27) and constitutes the first significant use of steam-power. The *trompe*, invented in Italy in the mid-sixteenth century, found wide application in the Catalan forge used by the iron smelters of the Pyrenees. It was essentially a water aspirator feeding into a closed wind-chest from which the expelled air was

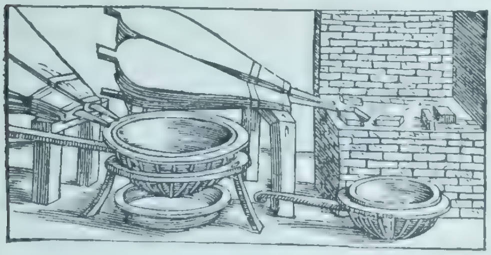

FIGURE 25—*Arrangement for melting metal in a casting-ladle. 1540.*

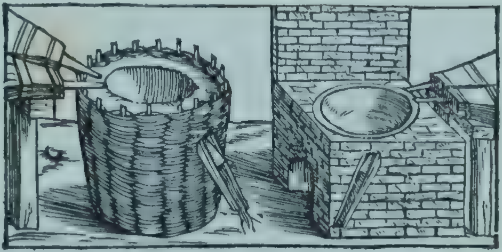

FIGURE 26—*Stationary melting-hearths, both arranged for bottom-tapping. 1540.*

led by a pipe to the tuyère (figure 28). Giambattista della Porta (1588) seems the first to mention this device, reporting that he had seen it in Rome and that its blast was suitable for brass- and iron-smelting furnaces.

For baking moulds and many miscellaneous purposes, Biringuccio built a furnace of bricks arranged in open checker-work to hold the fuel and allow ingress of air. Cellini used a furnace of this kind in preference to a forge even for melting gold and silver in crucibles. Operations calling for prolonged heating must have been very tedious before the invention of a self-stoking furnace. In metallurgical literature it is Ercker who first describes a gravity-stoked athanor which needed to be filled with charcoal only once a day (figure 29). The principle of a hopper from which fuel would descend continuously into the combustion zone to keep a steady fire was possible only for relatively low temperature operations, and

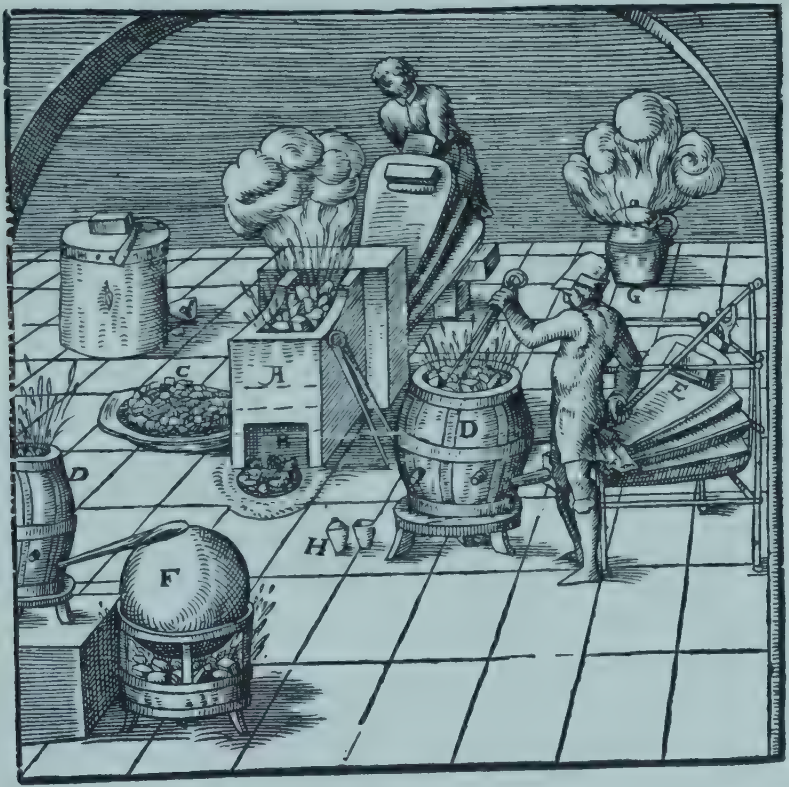

FIGURE 27—*Furnaces for the crucible-assay of copper ores (cf figure 24).* (A, D) *Furnaces;* (C) *crushed ore;* (E) *lever-operated bellows;* (F) *steam aeolipile used instead of bellows;* (G) *pot in which flux is prepared;* H, *assay-crucibles. 1574.*

these furnaces were used for processes like cementation, distillation, and evaporation. Operations demanding slowly increasing heat were effected by placing the crucible in the centre of a ring of coals which was gradually raked nearer and nearer (figure 30).

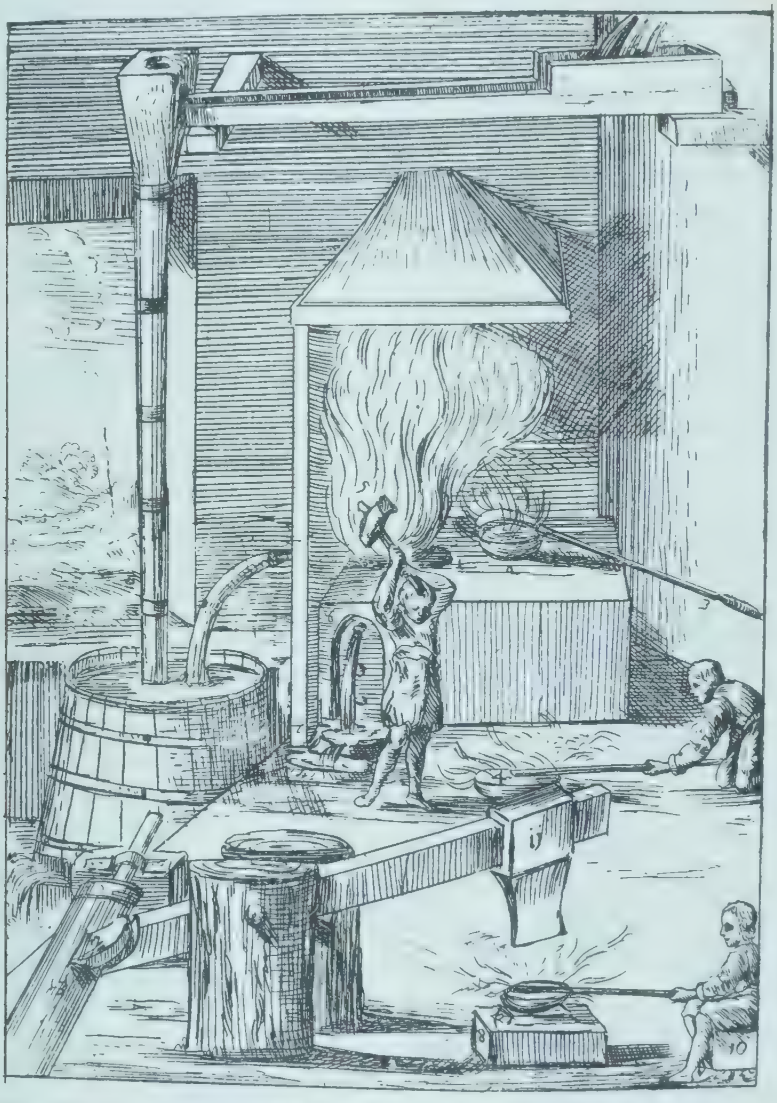

FIGURE 28—*The* trompe *used to blow a forge fire. Note the tilt-hammer in the foreground. 1678.*

The reverberatory furnace was of great importance for melting the large amounts of metal needed for cannon- and bell-founding. Leonardo da Vinci has several sketches of such furnaces, but Biringuccio and Cellini supply the first detailed descriptions (figures 16, 31). These furnaces were rather like present-day reverberatory furnaces except for the lack of a chimney to enhance the draught; the products of combustion escaped through small vents above the doors. It was recognized that copper could not be melted in a reverberatory furnace but had first to be alloyed with tin in a crucible-furnace of some kind. Biringuccio describes a kind of reverberatory furnace arranged so to carry the flame as to melt the cracked part only of a bell in order to repair it.

Solar furnaces, referred to as scientific wonders in antiquity, had become important possessions of scientific academies by the eighteenth century. Biringuccio mentions a German mirror about a foot in diameter capable of melting a gold ducat. Glauber (1651) specifically relates the amount of heat concentrated to the diameter, and says that a mirror of one span in diameter burns wood, of two spans melts tin, lead, or bismuth, of four or five spans melts gold and silver and softens iron sufficiently for forging [27]. Robert Hooke developed this concept further, and proposed to use the necessary aperture as a quantitative index of the degree of heat necessary to achieve various effects.

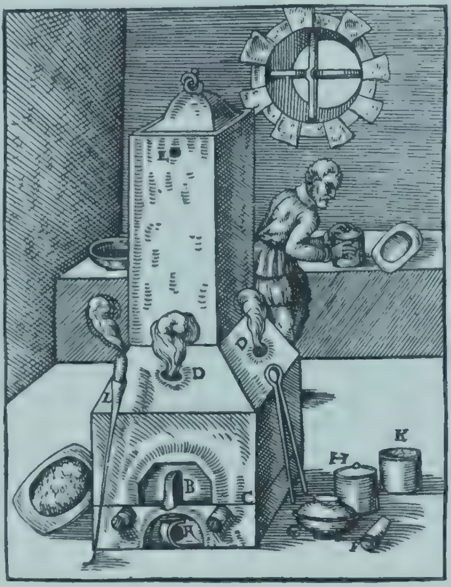

FIGURE 29—*Self-stoking furnace used for cementation.* (A, B) *Lower and upper mouth holes;* (C) *line where bottom plate rests on iron bars;* (D) *vents;* (F) *vent-plug;* (G) *scorifier;* (H, K) *pots for cementation. 1574.*

The blowpipe is still used by modern primitives to blow a charcoal fire for smelting and crucible-melting operations, as it was in ancient Egypt (vol I, figure 384). Its use for more delicate heating, as an adjunct to the hearth in a goldsmith's shop, is depicted in a Pompeian fresco, and it was probably goldsmiths who first applied it to the flame of a lamp to obtain an intense, highly localized heat. Robert Boyle (1685) used 'a small crooked pipe of metal or glass such as tradesmen . . . call a blowpipe' with a lamp or candle to melt not only the more fusible metals but even copper itself [44]. The delightful scientific art of blow-pipe analysis was beginning. A blast-lamp, consisting of an oil-lamp with a jet of air from foot-bellows, was illustrated by Kunckel (1679), who suggested its use for testing ores [45]. Early in the eighteenth century it was well established for local heating, as in soldering and enamelling metals and making coloured glass beads.

The annealing of rolled strip for coining operations, and of coiled drawn wire, was generally done with the simplest of devices, the metal being embedded directly in a pile of glowing charcoal on a flat grid. When closely uniform results were required, as in blanching coins, the fuel and coins were placed together in a kind of warming-pan and tossed frequently in the air to maintain uniformity.

X. METALLURGY AS A SCIENCE

This volume marks the transition from the purely empirical knowledge of processes and materials to the beginning of a scientific understanding of them. The great sixteenth-century works on metals have many quantitative aspects derived from experience, but make no effort to elucidate theory. To discern any theoretical metallurgical considerations of lasting importance we must await the eighteenth century. However, the great physicists and chemists of the seventeenth century consulted craftsmen, and Boyle, Hooke, and Glauber in particular appreciated the two-way interdependence of science and the arts.

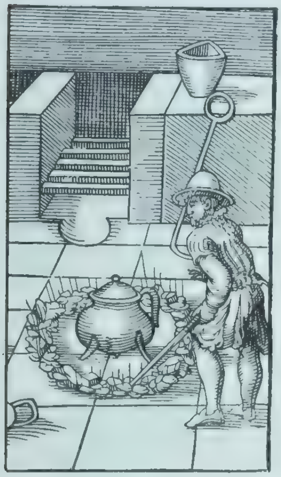

FIGURE 30—*Ring of coals used to increase heat gradually in the pot. 1574.*

Many of the interesting properties of metals and alloys were known in classical antiquity. Constitution diagrams could not, of course, be expected before the invention of a thermometric scale, but the essential phenomena were familiar enough: the depression of the melting-point of mixtures of metals and the proportions that yield eutectics of minimum melting-point, the immiscibility of some molten metals and the partition of solutes between the two liquids, the difference in composition between solid and liquid, the existence of terminal and intermediate solid solutions, and the formation of intermetallic compounds. That cold-working made metals hard and that annealing softened them had been known for millennia. Changes in properties, resulting from transformation or solubility changes, were produced even though not understood. The differing affinities of metals for each other and for non-metals were the very basis of refining and assaying. The existence of something like an electrochemical series was implicit in the knowledge that metals could replace each other sequentially from solutions of their salts. Diffusion in solids was utilized in making steel, cementing gold, and blanching silver. The relations between structure and properties were utilized daily in fracture-tests for quality and as a guide for composition or heat-treatment.

Both the followers of Descartes (1596–1650) and the opposing atomists were deeply concerned with the structure of matter, and their writings contain remarkably prescient remarks concerning the dependence of the properties of metals on the disposition of their component parts. Though there is much confusion as to the nature of the minute structure of matter (for phenomena due to interatomic forces are hopelessly intermixed with those due to microcrystals) there is nevertheless a clear concept of a metal as composed of parts which can slide over each other without losing their attraction, which are agitated by heat, and which can interdiffuse. The physical phenomena, however, were too complex for easy reduction to a quantitative scheme.

The phlogiston theory, which first appeared clearly in a metallurgical work, was the key doctrine of eighteenth-century chemistry. It was in essence an attempt to combine corpuscular theory with the ideas summarized in the theory of elements of the old chemists. By stimulating experiment it resulted in the accumulation of facts that eventually led to its displacement and the revival of atomistic ideas.

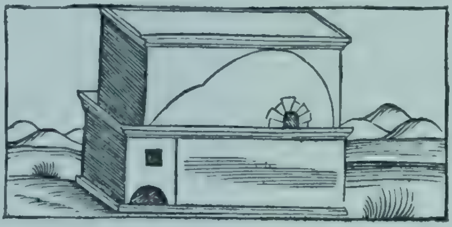

FIGURE 31—*Exterior view of reverberatory furnace used for melting bronze. 1540.*

The structure of metals as seen in fractures was commonly used to control craftsmen's operations. Savot (1627) remarks that 'bellfounders judge the quantity of tin which they should put in [bell-metal] by breaking a piece of the material before they cast it . . . , because if they find the grain too large they put in more tin; and if it is too fine they augment the copper' [61]. The learned blacksmith Jousse (1627) devoted several chapters to the recognition of good iron or steel, chiefly on the basis of fracture [17]. Boyle (1672) observed the crystalline facets of a fractured cast lump of bismuth and speculated on the mechanism of solidification [46]. The microscopist Henry Power records (1664) the first observations of metal under the microscope: 'Look at a polished piece [of gold, silver, steel, copper, tin or lead] and you shall see them all full of fissures, cavities and asperities and irregularities; but least of all in lead which is the closest and most compact solid body probably in the world' [47]. His examination of the sparks struck from steel inspired Hooke's discussion of their nature in his *Micrographia* (1665). Despite Réaumur's important efforts to understand the structure of metals on the basis of intercrystalline and transcrystalline fractures, it remained for the nineteenth century to realize the nature of polycrystalline materials.

The earliest physical property of metals to be quantitatively measured was density. There is an eleventh- or twelfth-century list of weights relative to wax compiled in order that the founder might know how much metal to melt. By the seventeenth century extensive tables of similar data become common in mathematicians' works, for example those of Napier (1617) [48] and Mersenne (1644) [49]. Caswell (1693) lists new measurements of the densities of twenty-nine metallic materials to five significant (?) figures [50].

Studies of the density of alloys were used in the first attempts to understand the nature of the interaction of metals. The experiment of Archimedes with the crown of Hiero will be recalled. In the Middle Ages it was assumed that a given weight of metal occupies the same volume in an alloy as when pure. Glauber showed that this was not true for copper and tin alloys, and believed that one metal could fill interstices between the parts of another. Perrault (1680) first recorded the increase in volume of steel on hardening [51]. In 1679 and 1680 the Royal Society studied 50–50 alloys of the various possible combinations of copper, tin, lead, silver, and antimony, noting their obvious qualities and their densities [29]. The alloy was generally of higher density than the theoretical mixture. This was explained by analogy with a mixture of shot of different sizes. Actually, most of the differences resulted from the varying soundness of the castings.

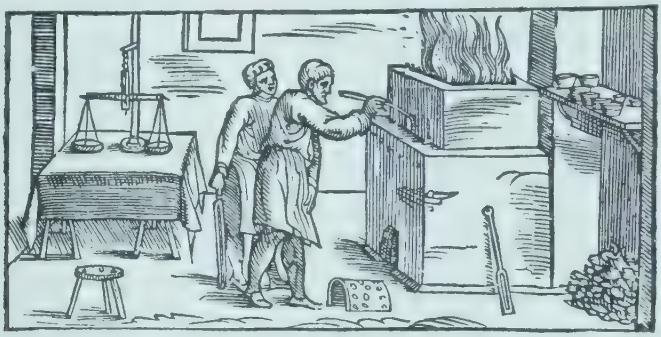

FIGURE 32—*Assay-laboratory, showing balance, muffle furnace for cupelling, ingot-mould, &c. 1540.*

Metals were used for engineering long before their strength was quantitatively measured. Music inspired[1] the first serious tests of tensile properties, made by Mersenne (1636) [52]. He reports that wires $\frac{1}{72}$-inch in diameter of gold, silver, copper, and iron fractured at 23, 23, 18½, and 19 lb respectively. These are much higher than today's figures, with the possible exception of iron if somewhat carbonized. Mersenne also records the density and natural frequency of hemispherical bells of many metals and alloys, thus giving for the first time a measured property related to elastic modulus. From Galileo (1638) on, those concerned with the formal science of the strength of materials were more interested in mathematical elasticity than in the realities of strength, though Galileo cites as an example a copper wire, a cubit long and weighing 1 oz, which could support 50 lb before breaking—about 6450 lb per sq in [53]. In 1662 Croone carried out before the Royal Society tests on silver wires $\frac{1}{6}$- and $\frac{1}{16}$-inch in diameter, but the experiments were abandoned. Not until Musschenbroek began his important investigations in 1729 was there further study of the problem.

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[1] Thus repaying music's debt to metallurgy, for, according to the medieval *Speculum humanae salvationis*, music itself originated in the forge of Tubal Cain when his brother Jubal contemplated the pleasant rhythmic noise of the hammer on the anvil.

XI. ASSAYING

In the sixteenth century there was no field of applied science more advanced than that of assaying. By centuries of purely empirical experiment precise methods had been developed for quantitative analysis in circumstances where it was economically justified. The assayer excelled the alchemist in all but the desire for a systematized philosophy. Unlike the alchemist he recorded his procedures in language for all to understand, and was essentially quantitative in outlook. The techniques for the assaying of ores and metals containing gold and silver had so developed that they were changed only in incidental details until the present century. Conversely, assaying for the base metals was relatively unimportant and had been poorly developed.

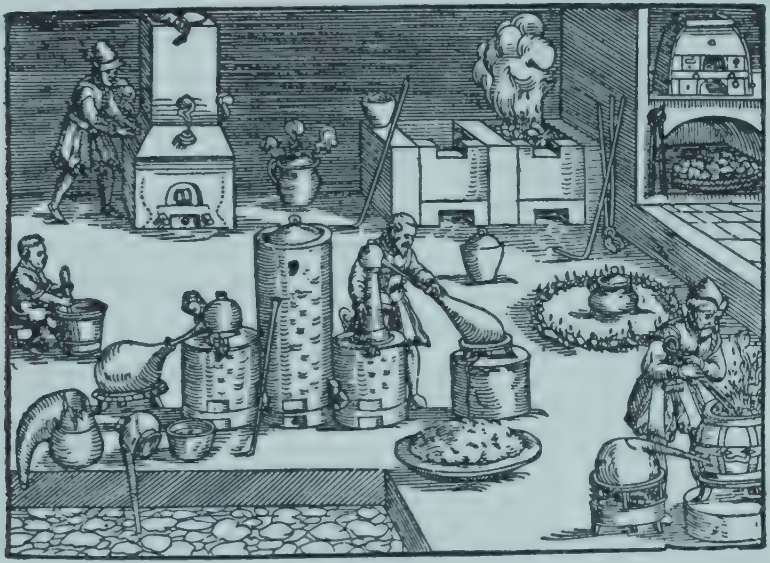

FIGURE 33—*Assay-laboratory with furnaces, distillation vessels, and so on.* 1574

The printed literature on assaying begins with the anonymous *Probierbüchlein*, (Magdeburg 1524) [1]. There are extensive chapters on the subject in Biringuccio and Agricola, while Ercker's volume is largely devoted to assaying. Thereafter, except for minor works [54], original writing on assaying ceased until Boizard

(1696) reported the practice in the Paris mint [41], and Cramer (1739) for the first time attempted to combine the empirical knowledge of the assayer with growing chemical theory [55].

Assaying had two main functions: the examination of ores to determine the possibility of profitably working them, and the examination of coins and jewelry to determine their quality and to detect fraud. The early assaying methods were not applied, as is modern chemical analysis, to determine the suitability of a material for engineering purposes.

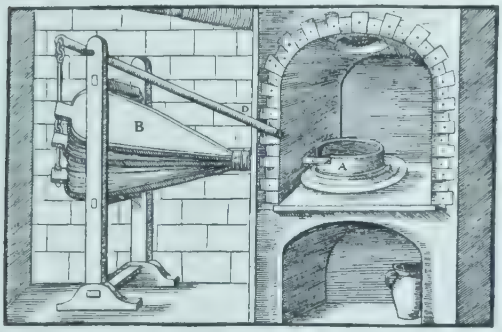

FIGURE 34—*Forge fire adapted for crucible-melting.* (A) *Iron hoop containing fuel;* (B) *lever-operated double bellows. 1556.*

The assayer's equipment. In addition to the wind- and muffle-furnaces (figures 32, 33) the assayer also used the forge fire, adapted for melting metals in a crucible (figure 34). The muffle-furnace for scorification and cupellation was built either entirely of fireclay, reinforced with iron rods or external iron straps, or of fireclay applied to a sheet iron shell. The muffle itself was initially merely a little clay arch with holes in the sides and back (figure 35) resting on a fire-brick, but Schreittmann (1578) shows the modern closed form [54]. Crucibles were moulded from fireclay either in hand-moulds or in a press (figure 36).

The assayer's utensils are notable for their satisfying shapes, which resulted partly from proper adaptation to function. Many are closely similar to those still in use. Though cheap glazed ceramics were used whenever possible for handling liquids, the assayer used glass extensively for distillation apparatus and for the delicate operations of parting (figure 37).

Cupels were very important to the assayer. They were made chiefly of levigated wood-ashes, with a facing of extremely fine bone-ash. The facing ashes are particularly important since they come into contact with the bead of metal. According to Ercker, they are best made of the bones of a calf's head, especially the forehead, although other assay books list various preferences, most commonly the ashes of fish-bone or horn. The cupels, of various sizes, were made by pounding the moistened ashes in brass or wood moulds (figure 38).

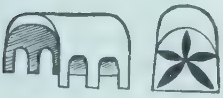

FIGURE 35—*Side and rear views of muffle for cupelling furnace. 1533.*

The assayer needed three separate balances, which were usually of the same type but of different capacity and sensitivity, the best showing about 0·1 mg. All three had beam-lifting devices to protect the knife-edges from shock (vol II, figure 678). The assayer had to know how to make his own balances, though he undoubtedly often bought them. There are excellent descriptions of the adjustment of the balances, reflecting a complete understanding of the principles involved, in both Ercker and Schreittmann.

The weights of the assayer were usually not those legal for trade, but miniature sets planned to give a reasonable size of sample for assay. These developed partly because no sufficiently small units existed in the legal systems and a cumbersome fractional designation would have been needed, but principally because the miniature weights avoided calculation since they maintained the proper ratios between the multitudinous units in vogue. The assayer had to have several sets of weights for different purposes (assay of ore, gold, silver, or copper). He usually made his own, either by starting with the smallest piece that his balance could detect and building up from this, or by starting from the biggest weight and successively subdividing by various tricks. A single set of weights usually contained from nine to sixteen pieces.

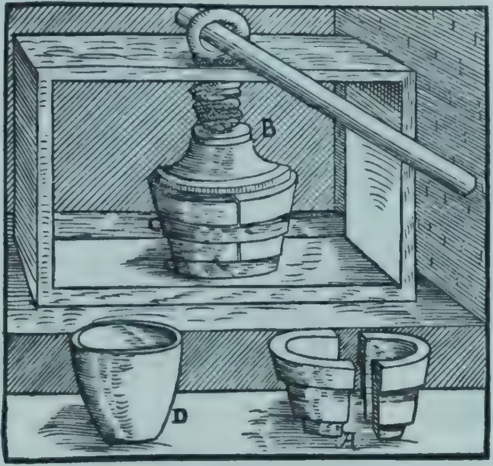

FIGURE 36—*Mould and screw-press for making crucibles.* (A) *Lower section of two-piece wooden mould;* (B) *the complete mould, showing the shaping of the crucible;* (C) *iron retaining hoop;* (D) *crucible. 1574.*

One assayer, Schreittmann (1578), developed a system of weights that deserves an important place in the history of metrology [54]. It is nothing less than a comprehensive decimal system adapted to give proper equivalents for all the fractional weights—sixteenths, twelfths, quarters, and thirds—that were involved in the various assay systems. He starts logically with weights smaller than can be detected with his assay-balance, and his first actual piece is ten of these units, which he calls *elementlin oder atomi*, *stüplin oder minutslin*. From this he builds up to 20, 30, and 40, then 100, 200, 300, and 400 and so on in thousands, ten thousands, and hundred thousands. He states that a legal pound is 1 106 920 units, thus one unit equalled 0·42 mg. Schreittmann gives many examples of computing assays in various systems by his new scheme. The fact that assays had to be reported in conventional units meant that the advantage of his system was for a time largely theoretical; nevertheless, it has in it most of the virtues of subsequent decimal systems and is an important precursor of the decimal fractional division of weights and measures proposed by Simon Stevin (*De thiende*, 1585) and the integrated decimal metric units of the French Republic.

Assaying of ores. Relatively little attention was paid by the early assayers to the assaying of base metal ores. Biringuccio, for example, states merely that base metal ores are assayed by fusion exactly as a larger quantity would be treated. Agricola assays lead ore by mixing a crushed sample with borax and placing it in a lump of charcoal in a crucible, while tin ore, after roasting and crushing, is mixed with borax and placed in a hole in a piece of charcoal. Bismuth is merely melted out of its ore, and mercury distilled out. Iron ore is first magnetically separated, then melted with saltpetre in a crucible in a blacksmith's forge.

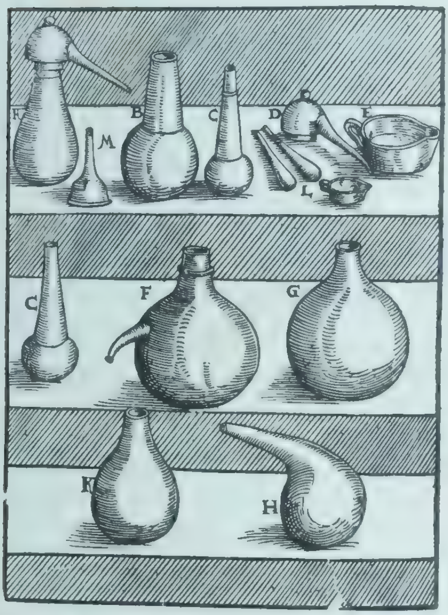

FIGURE 37—*Assayers' glassware and pottery vessels.* (A) *Coated glass flask, with still-head;* (B, C) *coated flasks;* (D) *still-head;* (E) *pourer;* (F) *receiver used in fractional distillation;* (G) *ordinary receiver;* (H) *earthenware retort;* (K) *earthenware pot;* (L) *small flasks;* (M) *glass funnel. 1574.*

Not until Ercker (1574) is there evidence of proper provision of a reducing agent. In assaying refractory copper ores, he says, it is necessary to roast thoroughly, then grind and mix with black flux (p 63) and some sandiver[1] before melting in a crucible to yield the metal. He assays for matte production by melting the ore with the reducing flux, without a previous roasting. He also describes the assay of copper, tin, and lead ore by smelting samples weighing a pound or so in a little laboratory blast-furnace in direct contact with charcoal, the metal being collected in a blast-hearth at the bottom. All early assayers tend thus to make their methods correspond on a small scale to actual production, and preferred to have results indicating practical yields rather than the true content of metal. Copper matte and black copper were assayed for refined copper by exposing the molten material in a scorifier to a blast of air until the surface showed the proper *Blick* (flash), the practical end-point (p 64).

Galena ores were assayed for lead by Ercker by mixing with the black flux and a small amount of iron filings, the iron removing the sulphur. Intractable lead ores were first roasted before melting with the flux and the iron filings were omitted. A simple assay is described that can be done without any furnace, simply by mixing the roasted ore with saltpetre and charcoal, a mixture which, once ignited, melts by itself.

[1] A neutral salt skimmed off the surface of melted glass. It is sometimes known as glass-gall.

In practice, trial in a smith's forge would be the most important assay of iron ores. Ercker suggests a magnetic assay for iron ores and remarks that some ores become magnetic only after roasting. Schindler (1687) is the first assayer to give a method of assaying iron ore by fusion with reducing material to give a regulus of cast iron [54].

The fluxes for the assay of precious metal ores contained such ingredients as silica pebbles, glass, salt, sandiver, borax, or *caput mortuum*,[1] with a collector which was almost always lead. For many purposes saltpetre was also added. Unless lead was present in the ore, it was added in the form of litharge. The most important single flux was the black flux, made by igniting a mixture of crude tartar and saltpetre with a piece of glowing charcoal. The materials reacted leaving a blackish mass, consisting of a mixture of potassium nitrite, potassium carbonate, and carbon.

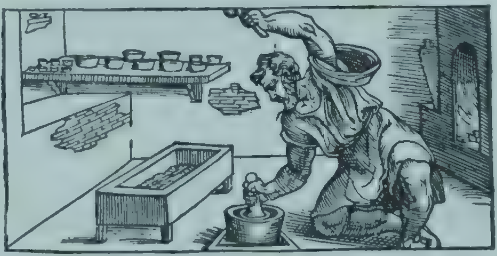

FIGURE 38—*Moulding cupels by hand. 1540.*

In no field does Ercker's superiority appear more than in his attitude towards fluxes. The *Probierbüchlein* quotes eight different varieties of fluxes, while Agricola lists no fewer than eighteen. Ercker, however, uses only two, either the standard black flux or a lead silicate glass, adding iron filings for lead sulphide ores.

A fine sixteenth-century English account of assaying copper and other base-metal ores in Cumberland has been found recently in the notebook of Daniel Hochstetter, one of the principal German experts who were brought over to work the deposits there [63]. Gabriel Plattes (1639)—the first man to publish a useful treatise in English on metallurgical matters—describes simple fireside assays of lead and copper ores [56]. Lead ore he merely mixes with iron filings and melts, though he remarks that a quarter of an ounce of sandiver and as much saltpetre will make it melt sooner and give a clean slag. Tin and copper ores are similarly treated but without the iron filings or any reducing agent! As with most of the early assayers, he gives methods for extracting silver from iron, which must have been a rather profitless operation except on objects inlaid or encrusted with silver. Barba (1640) advises the use of litharge alone as a flux for crucible assay, claiming that other additions are unnecessary [7].

Another common method of assay for ores containing gold and silver was by scorification, in which the ore mixed with flux was placed on the top of an open bath of lead in a scorifier exposed to air under a muffle. Much of the lead oxidized away, but the residual button contained the whole of the precious metal.

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[1] An alchemical name for the earthy residue left in the retort after distillation, usually of materials to give nitric acid. It would consist principally of ferric oxide and potassium sulphate.

Samuel Zimmerman (1573) suggests, apparently for the first time, a wet method of assay. He says that gold or silver can be extracted from an ore, after roasting with lime if necessary, by extraction with *aqua regia* or *aqua fortis* respectively, the metal being precipitated from the solution with mercury or copper [62].

When assaying base metal ore the metallic product was weighed directly; for the precious metals the lead button from crucible or scorifier had to be cupelled.

Cupellation makes use of the resistance of the precious metals to oxidation, which distinguishes them from all other common metals. If a bath of impure lead is heated in air at a full red heat, the litharge formed by the oxidizing lead will dissolve the oxides of most other base metals, and the surface tension relations are such that the molten litharge will wet and soak into the ash of the cupel, while the metal will remain unabsorbed as a compact molten bead. The base metals continue to oxidize away until there remains nothing but a fine bead containing all the gold and silver originally present in the lead.

Cupellation still remains one of the most accurate assay methods, particularly for low concentrations. Though the process is chemically simple it calls for skilled craftsmanship, and the old writers seem to delight in attempting to pass on their knowledge. In cupellation the cupels were placed under a muffle in a furnace and annealed for half an hour before adding either the lead button from a scorification or crucible-fusion of ore, or a bullet of lead to which a weighed metal sample was added. The largest cupels held about 2 oz of lead.

The importance of temperature control was well realized. The assay was usually started hot and finished cold. The operation was controlled by careful observation of the play of colours and the movement of litharge over the surface of the metal, and the formation of the delicate yellow litharge crystals on the cold parts of the cupel. To protect the assayer's eyes and face he commonly used a board with a slit in it through which he peered into the hot furnace (figure 41). Arphe (1572) thus describes the appearance of the lead on the cupel: 'During the process waters are seen on top of the assay rising from the border of the grain, but when the silver becomes fine it forms a cover of a matte appearance, without any gloss. This is a sign that all the lead has been absorbed in the cupel and has taken with it all the other metals except silver, or gold if the silver contained any. After the assay becomes covered, it uncovers again and remains shining bright and clean' [54]. This sudden brightening or flash (*Blick*) is the end-point of the operation.

In assaying bullion or base metal the operation was essentially the same. The weight of lead varied from four times the weight of the silver, if it was relatively pure, to as much as eighteen times for silver-bearing copper. The assayer knew that his lead contained silver and he prepared silver beads as blanks by cupellation of the amount of lead to be used in an assay, which beads were used as counterpoises during the weighing of the assay beads.

Parting. The beads from cupelling would contain both gold and silver if both were present in the sample. Though on a larger scale these two metals were separated with sulphur or antimony sulphide, for assay purposes nitric acid was always used. Beads containing less than a third of gold were hammered into a little strip and directly attacked with concentrated nitric acid. This left the gold behind in the form of a coherent piece, a loose sponge, or as fine particles, depending on the alloy-concentration and the strength of the acid. If too much gold is present the alloy remains unattacked, and for assay it was therefore diluted with silver. This operation, known as *inquartation*, generally aimed at producing a bead containing three times as much silver as gold, though both Arphe and Boizard recommend a 2 : 1 ratio.

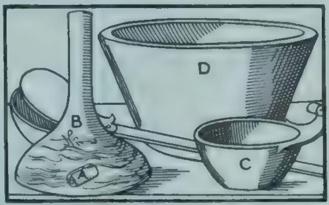

FIGURE 39—*Parting-flask* (B) *and annealing cups* (C, D). *A cornet* (A) *is immersed in the parting-acid. 1572.*

If the approximate composition of the gold was not known, it was tested by touchstone or by a trial parting, and silver was then added to give the proper ratio for the gold to remain in a porous but coherent form after acid treatment. The inquarted bead was hammered flat, coiled into a little spiral or cornet, and boiled with three successive lots of nitric acid in a little flask (figure 39), after which the residual gold was washed, transferred to a small crucible or silver cup to be annealed, and finally weighed. The present-day assayer does precisely the same.

Assayers generally made their own parting-acid, and Biringuccio, Ercker, and Agricola all devote pages to its manufacture. It was made by destructive distillation of saltpetre mixed with alum or vitriol in a still composed of a matrass, alembic-head, and receiver (figure 40). Before use in parting, the acid was always treated by dissolving a small amount of silver in a little acid and adding it to the rest until no further precipitate was formed. This was essential to remove chlorides, present as impurities, the presence of which would leave the parted gold heavily contaminated with silver chloride and in extreme cases would, as *aqua regia*, dissolve the gold itself instead of the silver.

Assay by touchstone is mentioned in Greek literature and was common in the sixteenth century, although it was quite properly regarded as only an approximate method (vol II, p 45).

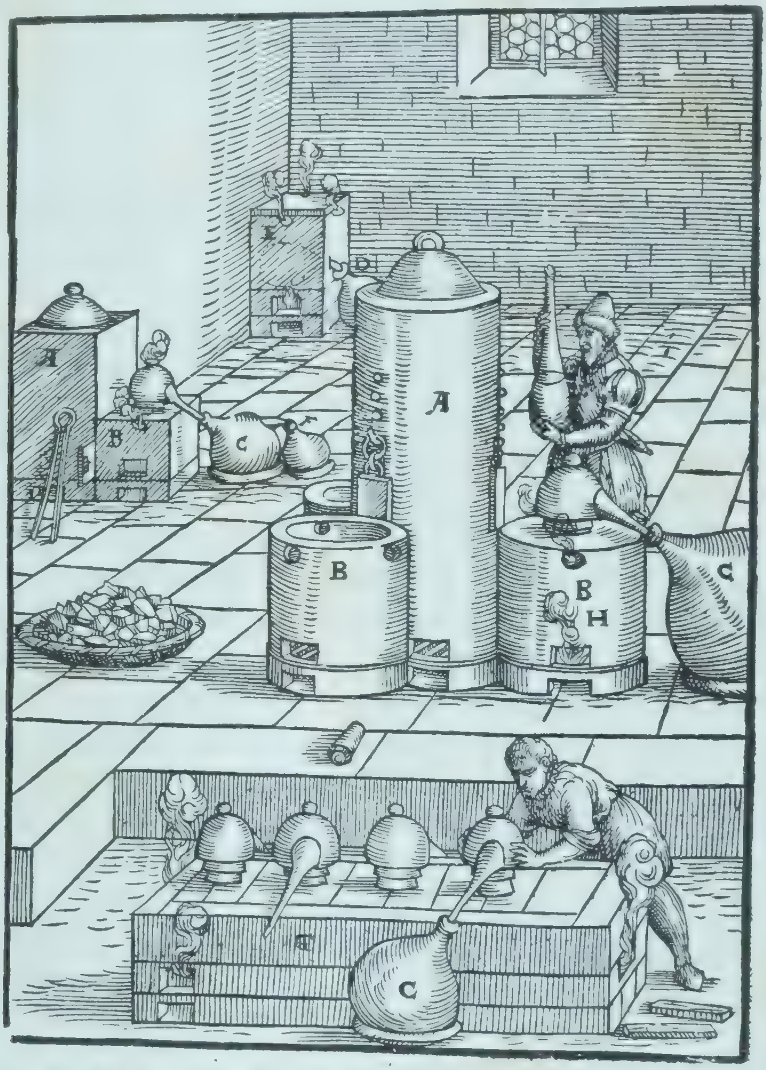

FIGURE 40—*Four types of furnace for distilling parting-acid.* (A) *Tower of 'slow Harry' furnace;* (B) *side chambers in which pots containing reagents are placed;* (C) *glass receivers;* (D) *earthenware vessel;* (E) *furnace used to heat a retort (shown within);* (F) *small receptacle connected to large receiver to make room for 'spirits' driven over from retort;* (G) *long furnace;* (H) *side chamber. 1574.*

Assay by density is not distinctly referred to as a method of assaying (otherwise than for merely checking identity, as by Archimedes, p 58) until the thirteenth century, when the pseudonymous treatise *Liber Archimedis de ponderibus* appeared [57]. Many variations on the principle are described thereafter, usually with confusion between volume- and weight-percentages of the components. A balance with a graduated beam and movable fulcrum for use in this type of study was described in the poem *Carmen de ponderibus* attributed to Priscian (sixth century A.D.; printed 1475) and in modified form in Galileo's first scientific paper (*c* 1586) [58]. Actually such balances would be hopelessly insensitive to small changes in composition.

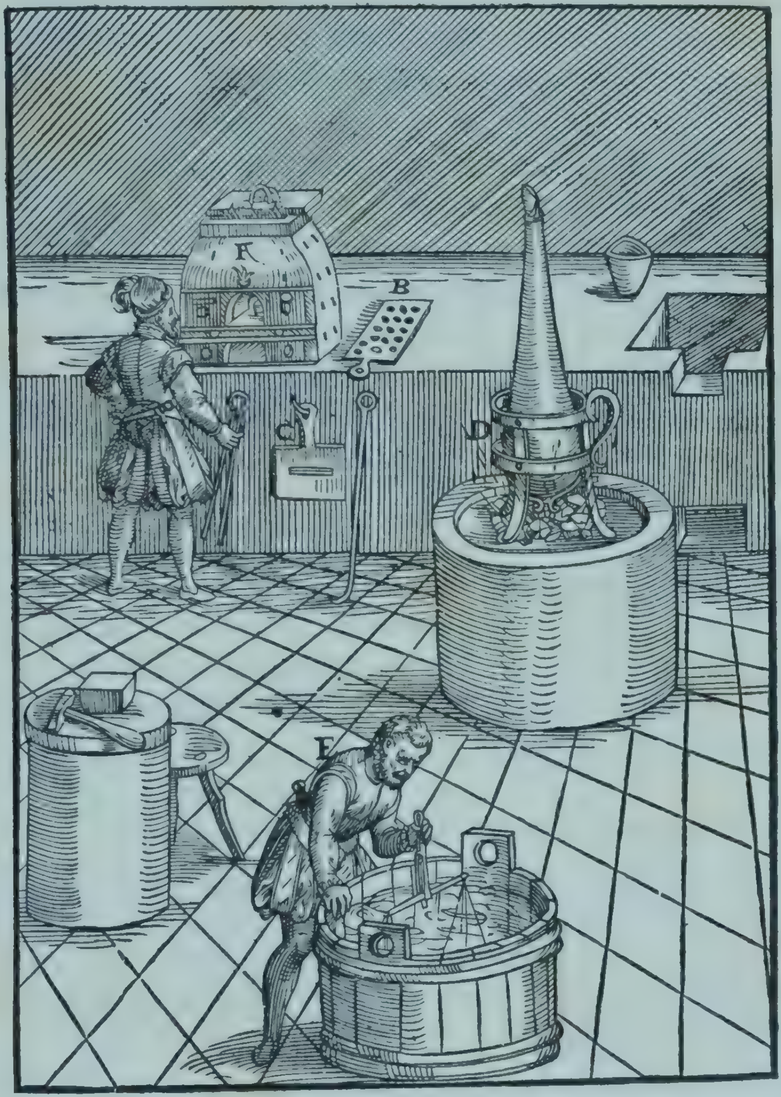

FIGURE 41—*Assay laboratory.* (A) *Furnace;* (B) *iron sheet on to which assays are poured;* (C) *implement with slit used in inspecting furnace to avoid damage to the eyes;* (D) *parting-flask on stand;* (E) *assay by water-displacement method on auriferous silver. 1574.*

An exact though tedious method is given by Ercker, who adjusts quantities of pure silver and pure gold granules counterpoising the sample to be assayed, until there is no change on immersing the balance in water (figure 41). He describes another method, using silver weights and determining the overweight on immersion in water, and a third method involving the comparison of the weights of equal lengths of wires of gold, silver, and the alloy, all drawn through the same die. Ercker, however, did not recommend these assays, for he knew that different samples even of a pure metal may differ in density. Porta (1589) [16] has still another variant, erroneously computed, while Boyle developed a simple hydrometer float (1675) for weighing above and below water [59]. He tested coins by direct comparison against standards, and used no assumed relation between density and composition.

The weight of a cast ball made in a standard mould was used by pewterers as a method of assay at least as early as the mid-fourteenth century. This was a simple acceptance or rejection test and although, in its actions against fraudulent pewterers, the Pewterers' Company records the excess weight over the standards, it records no attempt to relate this to actual composition until the comparatively late date of 1710 [32].

Various qualitative assay methods were well known, and are discussed in some detail by Glauber [60]. He uses the colour of both flame and fume as an indicator of metals and makes astute observations on the effect of impurities on the shape of drops of metals, which we now interpret in terms of surface tension. Eight years earlier Glauber had suggested qualitative assay by observing the colours produced by a sample of ore melted with glass, a method that was later to be refined into the borax bead test.

Metallurgy in the sixteenth and seventeenth centuries was much influenced by the wide distribution of printed books recording in detail the techniques and alloy compositions that had been in use for many centuries, for the subject then became of general interest to scholars and other citizens. The special properties of metals and their transformations were not ignored in the general spirit of inquiry that now prevailed.

With the foundation of the great learned societies in the mid-seventeenth century the practical knowledge of artisans attracted the interest of experimental philosophers, but practical knowledge continued far in advance of theory. Not until the eighteenth century was theoretical science in a position to aid practice in any but minor ways. Yet the methods of modern science were being begotten from this conjunction of philosophy with the practical observation and intuitive knowledge of those who actually handled the materials, and in the next century the increased understanding of the nature of metals and their reactions led naturally to improved processes and to materials better suited for the increasingly stringent demands of a more sophisticated engineering.

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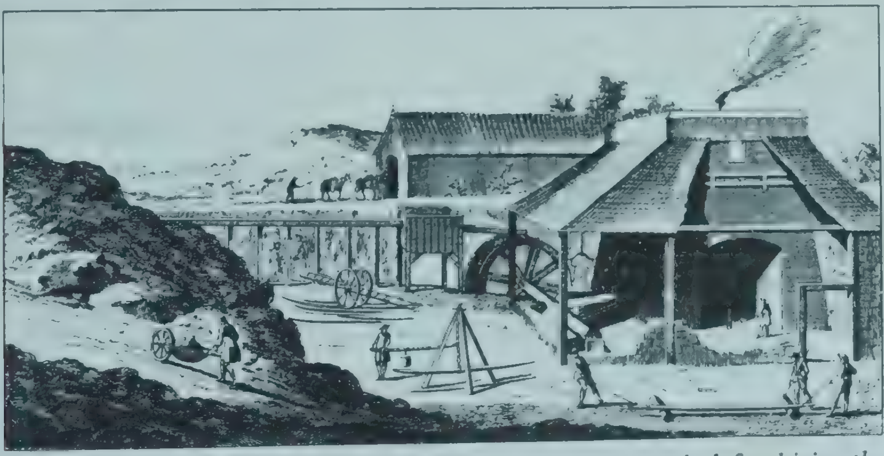

General view of a French ironworks in 1716, showing the water-wheel for driving the bellows, with its chute, the partly-sectioned building around the furnace, pigs of iron being transported and weighed, and men carrying away slag to the tip.

3

COAL MINING AND UTILIZATION

J. U. NEF

I. THE EARLY HISTORY OF COAL

It is impossible to say when coal was first deliberately burned. What is certain is that this mineral has played an important part in the development of western technology only in comparatively recent times, namely since the Middle Ages. Scientific interest in coal as a source of raw materials, not merely of heat, was a product of the nineteenth century.

All the societies that evolved before the Christian era in the Mediterranean basin and in the Near East had some recourse to the mineral wealth of the subsoil. But there have never been, at least since the dawn of recorded history, rich coal-seams near the surface in Egypt, north Africa, the Balkans, Asia Minor, Mesopotamia, or India. If coal, or at any rate lignite, was burned at all in these regions before the birth of Christ (and there is little convincing evidence that it was) it had certainly no part in shaping the technical development of ancient peoples. Here its history has to be distinguished sharply from that of metals such as copper, lead, iron, or even silver and gold, for the ores of all of these metals were dug in ancient times, and the technology of metallurgy has a very ancient and interesting history (vol I, ch 21; vol II, ch 2; vol III, ch 2). After the Hellenistic era the extension of Roman dominion beyond the Alps into northwestern Europe placed the technology and science of Graeco-Roman societies partly at the disposal both of settlers from southern Europe and other parts of the Roman Empire, and of the inhabitants conquered by the legions of Rome in Gaul and Britain. Both Gaul and Britain are distinguished from other parts of the empire—the Balkans, the Near East, and north Africa—by abundant outcropping coal-seams. Such seams were to be found to some extent at several places in southern and central France, and in much greater numbers along a strip of territory in the Low Countries that begins just west of Mons and runs in an easterly direction to Liége and onwards to Aachen (Aix-la-Chapelle).

The most abundant outcropping coal-seams were in Britain. It has been suggested by one scholar, on the basis of modern archaeological evidence, that after the Roman conquest coal was fairly extensively worked for a time at many places in England, particularly during the fourth century A.D. [1]. Such a high importance is, however, not usually allowed to the coal-workings of Roman Britain; and even if it were the case that mineral fuel was dug during the Roman occupation in most of those fields where the seams poked their way close to the surface, it is unlikely that coal had any appreciable influence in Graeco-Roman times upon technological processes—upon the structure of ovens, forges, and furnaces, upon the machinery used in industry, or upon the means of transporting commodities by land and sea in any part of Europe.

After the barbarian invasions from the east and north, verifiable historical references to the digging or the use of coal disappear, so far as both the European continent and Britain are concerned. From the sixth to the eleventh century there is apparently no mention of coal in the documents of medieval Europe. Nor have archaeologists, it seems, been able to offer any clear evidence that coal was worked during that period. There is nothing for coal comparable to the records we have concerning metallurgy, and iron metallurgy in particular, during these early centuries of medieval history. Foreigners and visitors from the south of Europe and from the Near East sometimes speak, not without awe, of the iron-work of the barbarians, particularly their weapons of war and above all their swords. They never mention the burning of coal.

In short, coal remained a closed chapter in western Europe until the twelfth and thirteenth centuries—if indeed, which is rather doubtful, it had ever been anything more than a footnote to a chapter.

Farther west still, across the Atlantic, on the huge continent of which the ancient and medieval peoples seem to have been unaware, no chapter was written by coal, not even a footnote, until after the European settlers began to come in during the sixteenth century. The rich early societies of South and Central America, and those particularly of Peru and Mexico, made some use of metal, but apparently none of coal. This is not surprising when we realize how poor these territories were in coal-resources as contrasted with North America, which was still in the hands of primitive tribes.

In the Far East the early history of coal was different. Marco Polo (1254?–?1324) was much struck when he discovered that in parts of China the natives were burning black stones as fuel. As an Italian, he had never seen this done before. While he probably would have been less astonished had he come from the Low Countries or from England, it appears that coal had been worked in China much more extensively than in Europe for many centuries. The question is how extensively and for what purposes coal had been burned. On these points the historians' answer must still be tentative. Joseph Needham has recently declared, 'It is certain that coal was used directly for smelting iron at least since the fourth century in China.' Needham seems to have compelling evidence that the smelting of iron ore was common in parts of China a great many centuries earlier than it was in Europe, partly because some Chinese ores could be melted at a considerably lower temperature than any European ones. But it does not necessarily follow that coal fuel was commonly used in the process. It has been suggested, on the other hand, that relevant passages in Chinese literature indicate nothing more than the use of coal in the manufacture of iron objects; such a use of coal in producing crude iron wares, for example·horse-shoes, was in other parts of the world frequently that to which coal was first put, coal being mixed with charcoal in the forge [2]. The substitution of coal for other fuels in the working of wrought iron in smithies presented no technical problems commensurable with those involved in the first smelting of the iron from ores. What is certain is that coal has been dug and used as fuel in China for two or three millennia. The Chinese made rather more of their coal resources than other peoples until the thirteenth, and possibly until the sixteenth, century.

In Europe, from the thirteenth to the middle of the sixteenth century, the coal resources of the Low Countries, especially those of the small principality of Liége, were those most exploited. Charles the Bold (1433–77), the fiery Duke of Burgundy, in his fury with the Liégeois, is said to have ordered his soldiers to erase the city from the map, and to have vowed that even its name should not be revived. Yet, in the decades following his death, Liége became one of the great European armouries. During the first half of the sixteenth century the output of coal in the region tripled or quadrupled [3] to provide fuel for the growing manufactures of iron and other metals into finished wares in the town itself and at many places up and down the wide, gently flowing river Meuse (figure 42). Liége coals were not quite carried to Newcastle; but this fuel from the land of 'Luick' did compete at Calais and other Channel ports with sea-coal brought from the Tyne. At Liége, long adits were driven to drain the coal-pits sunk in the hills above the town. They were planned systematically in such a way that the continuous flow from the underground passages, where the miners worked, provided the main water-supply of the city. The town had a double stake in the careful development of the technique of working coal. By the mid-sixteenth century the mounds of black earth thrown up beside the pits were hardly less prominent a sight for travellers than the spires of the churches. They were more portentous of the future that awaited the western people than the city halls, the courts of justice, and the merchant palaces that were rising in profusion [4].

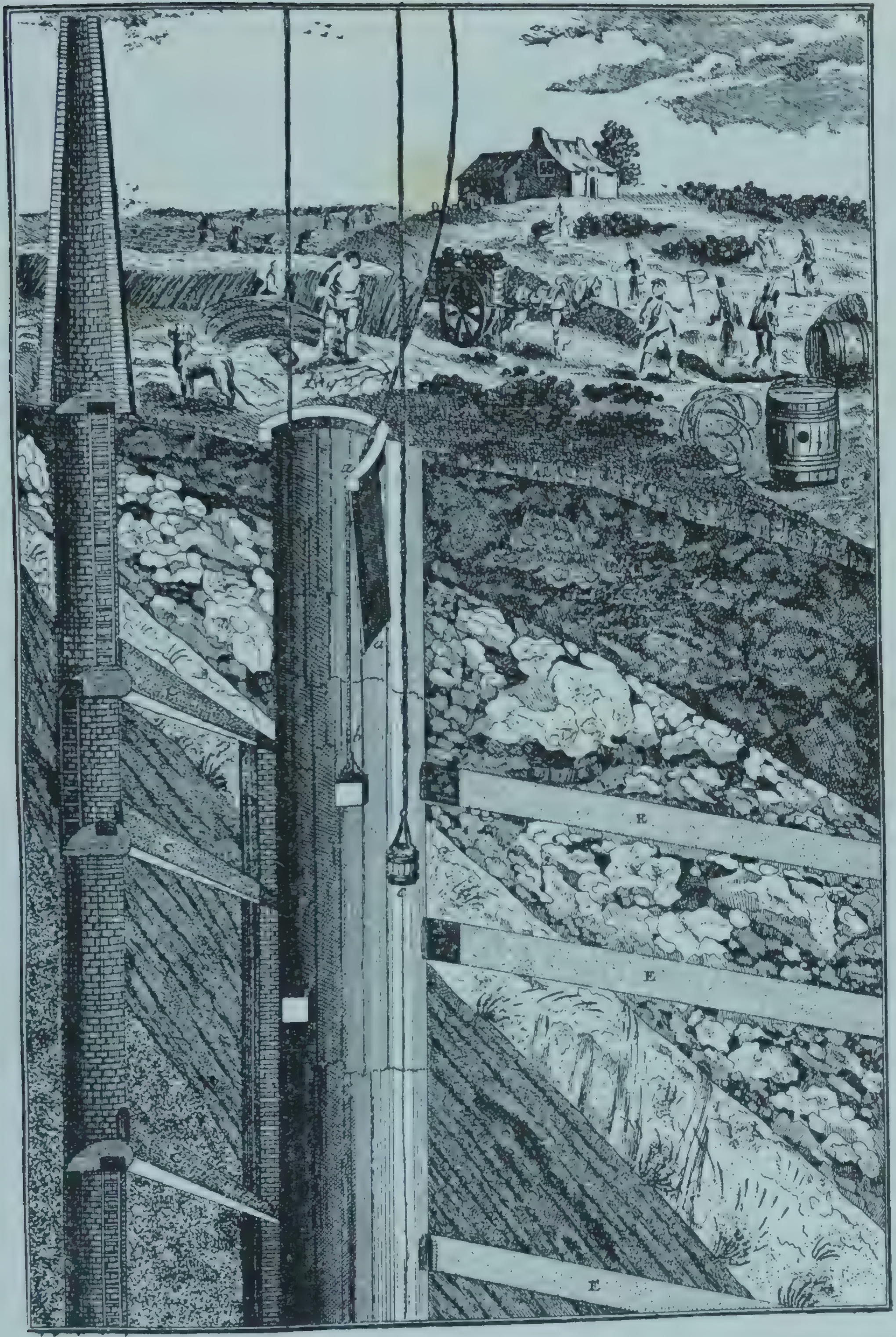

FIGURE 42—*Coal-mine in the Liége district.* (Centre) *Haulage shaft with galleries leading off;* (left) *ventilation shaft, with chimney and doors to shafts.* 1773.

II. THE BRITISH COAL INDUSTRY

It was just after this time that a great change occurred in the place of coal in technology, destined to have an immense influence upon the coming of the iron and steel and machine economy. While the reign of Elizabeth II seems to mark the end of English supremacy among the nations of the world in the exploitation of coal, the reign of Elizabeth I marked its beginning. From the end of the sixteenth century until the middle of the Victorian age, from about 1600 to 1860 or so, Great Britain was without a close rival when it came to the mining and use of mineral fuel. Already during the early decades of the seventeenth century coal came into widespread use, not only in the domestic hearths of the English and Scottish, and in their laundry-work and cooking, but in the extraction of salt and the manufacture of glass, bricks and tiles for building, anchors for ships, and

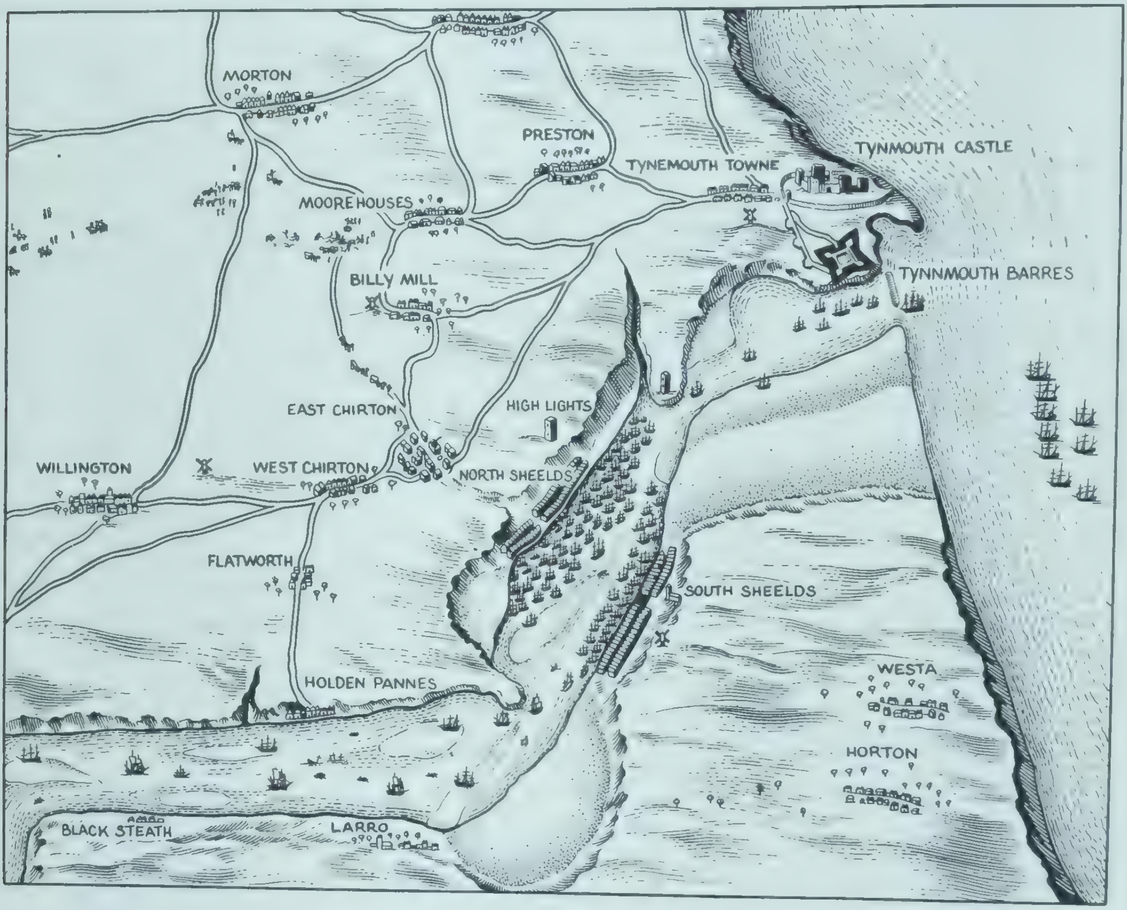

FIGURE 43—*Portion of a map of the mouth of the Tyne, showing colliers, salt-pans, etc. 1655.*

tobacco-pipes. The dyers, the hat-makers, the sugar-refiners, the brewers, who were growing very numerous especially in London and some provincial towns, and even some of the bakers of bread required coal. As early as the reign of James I (1603–25), the expansion of the English manufacture of alum, to supply the native dyeing industry with an essential mordant, came to depend upon the arrival of ship loads of coal from the north of England at ports along the Yorkshire coast, near newly discovered deposits of alumstone. In the year 1563–4 the shipments of coal from Newcastle-upon-Tyne amounted to 32 951 tons. A century later, in the year 1658–9, they had risen to 529 032 tons. Between about 1580, when Shakespeare is said to have settled in the capital, and the Restoration in 1660, the imports at London increased some twenty- to twenty-five-fold (figure 43) [5]. Foreigners who visited the rapidly growing city were astonished at the filthy smoke from tens of thousands of domestic fires and from hundreds of workshops. There was no spectacle like it anywhere else on earth. With its breweries, its soap- and starch-houses, its brick-kilns, sugar-refineries, earthenware works, and glass-furnaces, London seemed to some of these foreigners to have been rendered unfit for human habitation [6]. Even the English virtuoso John Evelyn (1620–1706) was repelled by the fog of smoke belching from the sooty throats of the new manufacturing shops, to hang over the metropolis and insinuate itself along the streets. He compared this new, dark London to 'the picture of Troy sacked by the Greeks, or the approaches of Mount Hecla' [7]. By the Restoration or very soon afterwards the small island of Great Britain, with its expanding mines in Scotland, Wales, and many parts of England, was producing in all probability some 2 m tons of coal annually, perhaps five times as much as all the rest of the world [8].

For the history of technology and science, which have so direct a bearing on the advent of the unique industrial civilization of our times, the great significance of this novel shift from a wood-burning to a coal-burning economy consisted in the new technological problems that were raised in an acute form in three domains: first, in the industrial use of coal; second, in the mining industry; and third, in the transport industry. Upon a solution of these problems the eventual adoption of a machine economy largely depended.

III. NEW USES FOR COAL FUEL

The pressure put upon the supplies of firewood and timber by the expansion of population, and by ship-building and other manufactures in England, had become so great by the end of Elizabeth I's reign that the prices of firewood in London and of many kinds of timber for construction-work had risen more than those of any other commodities for which modern statisticians have gathered the figures [9]. In a number of industries, such as the evaporation of salt water to produce salt, the heating of solutions of alumstone to produce alum, in the making of lime, and in the baking of bricks, the substitution of coal for earlier fuels, particularly for firewood and charcoal, could be effected without any great change in the processes of manufacture. There were also, however, many industries in which the adoption of coal fuel was possible only if new methods of manufacture were invented. Glass-making is an important case in point (pp 220–1). Between about 1605 and 1612 a new type of furnace was devised. In it the raw materials were heated in closed crucibles, and so were protected from the nauseous fumes and flames of the burning coal [10]. While the new furnaces rendered it possible to produce sheet glass—serviceable for such commodities as plain window-panes—in larger quantities than ever before, it made impracticable the blowing of glass in the flames, an art in which the Italians and, under Italian influence, most continental peoples excelled.

Thus the need for substituting coal for wood as fuel tended to encourage a concentration of capital and labour upon types of technology in which the primary purpose of invention was to increase the output of cheap commodities, rather than to improve the quality of more valuable, and often very beautiful, commodities.

The future of an expanding manufacture of iron in the British Isles after about 1600 came to be bound up with the replacement of wood by coal in the furnaces and the forges at which pig iron was converted into bar iron, some of which was reconverted into rods at slitting-mills. Charcoal for iron metallurgy was not rising in price nearly so rapidly as firewood and timber during the late sixteenth and early seventeenth centuries, because, unlike firewood and timber for building, it was not carted for long distances to the centres of population and of industry, but was made and burned mainly at the place where the trees were felled. Parts of Great Britain—for example, the Forest of Dean—had abundant forests, and ironmasters built new furnaces and forges where plenty of wood was to be had for charcoal (figure 416). But this involved a movement away from the centres of demand; it added to the expense of setting up metallurgical plant and of marketing the output. The advantages that would follow the adoption of coal fuel in metallurgy were recognized at the beginning of the seventeenth century, and the very slow growth in the output of cast and bar iron in Great Britain during the later seventeenth and much of the eighteenth century must be attributed in a considerable degree to the stubborn technical difficulties that had to be overcome before coal replaced wood generally in iron metallurgy.

While coal had been used earlier in small quantities for making crude iron wares from wrought iron, no success had apparently been achieved in Europe at the end of the sixteenth century in the substitution of coal for wood in smelting any metallic ores. If, as has been suggested, such progress had been made much earlier in China in the smelting of iron ore, it was not from China that the western peoples learned how to use coal instead of wood in metallurgy.

How, then, did the conquest by coal of the smelting-processes in Great Britain come about? Two men claimed to have solved the problem of substituting coal for charcoal as fuel in the blast-furnaces at which iron ore was smelted and run into moulds, at the very beginning of the seventeenth century. Simon Sturtevant, who was apparently of Dutch origin, and John Rovenzon published treatises on metallurgy in 1612 and 1613 advocating the adoption of coal-burning blast furnaces, which they suggest are feasible though they fail to describe the processes that they profess to have invented to bring it about. Their methods, like those of many other inventors during the decades that followed, proved unsuccessful.

As the technical obstacles to the substitution of coal for wood had been overcome in glass-making at about the time that Sturtevant and Rovenzon published their treatises, and as a method, probably inspired by this success in glass-making, was devised by William Ellyott and Mathias Mersey in 1614 for using coal as fuel in the manufacture of steel from bar iron, it is puzzling why the general success of the substitution in iron metallurgy should have been delayed for several generations.

During the late sixteenth century the production of wrought iron by the indirect process (in which the iron was run in liquid form from the blast-furnace into moulds, known as pigs, to be converted into wrought iron by heating and hammering at forges) was coming into widespread use, particularly in northern Europe, in the Low Countries (plate 3), in Sweden, and in Britain. The problem of substituting coal for charcoal as fuel was complicated because the ore and iron had often to pass through a number of stages before the metal was ready in the form of bars or rods for smiths to forge into finished products. It was necessary for coal to make the conquest of all these stages. Each stage presented its own special problems, and in each the simple replacement of charcoal or wood was impracticable because, as in glass-making, the mineral fuel damaged the material.

Early in the seventeenth century a little coal was certainly mixed with charcoal as fuel for calcining the ore in preparation for the blast-furnaces, and also at both the finery and the chafery—the two types of forge used for manufacturing bar iron from pig or cast iron [11]. But, in spite of the claims of Sturtevant, Rovenzon, and others, the conquest of the blast-furnace by coal fuel was long delayed. It was finally brought about indirectly, as a result perhaps of efforts to solve the problems of substituting coal for charcoal and wood in the brewing industry. The use of coal at the breweries themselves seems to have presented no serious problems, and some London brewers began to burn coal at least as early as the reign of James I [12]. In 1637 four out of five of the breweries in Westminster were said to burn ordinary coal instead of wood [13].

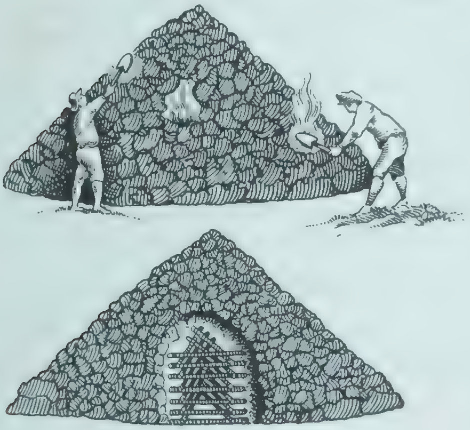

FIGURE 44—*Coke-burning, 1773.*

It was in the drying of malt, necessary for certain brews, that the new fuel transmitted its obnoxious properties indirectly to the taste of the beer. Few persons could bear to drink beer brewed from malt dried with raw coal. The idea of charring coal, as wood was charred to produce charcoal, to purge the mineral fuel of some of its impurities, may have occurred in 1603 to an ingenious promoter named Sir Hugh Platt (1552–1608), who supplied a recipe for making briquettes as a means of sweetening the domestic fires that caused so much distaste to sensitive noses in London [14]. But the early efforts to coke the coal failed. It was apparently in connexion with the drying of malt that success was first achieved, in Derbyshire about the time of the Civil War (1642–8). Beer brewed from malt dried with what were then called 'coaks' was pronounced sweet and pure (figure 44). The coke was made from a special kind of hard coal dug near Derby; and, as a result of the new discovery, Derbyshire beer became famous throughout England [15].

The same properties of raw coal that transmitted a disagreeable taste to the beer brewed from coal-dried malt caused it when used in blast-furnaces to damage the cast and pig iron, making it brittle and useless. Yet, curiously enough, it seems that half a century elapsed after coke was used in drying malt before it was successfully tried in a blast-furnace. Meanwhile, at the end of the seventeenth century, the invention of a new reverberatory furnace for smelting the ores of lead, and later those of tin and copper, made it possible to substitute raw coal for charcoal in these metallurgical processes. The first recorded successful experiment in using coke for smelting iron ore was at Broseley, in Shropshire, in 1709 [16], but this experiment did not at once bring about any widespread introduction of mineral fuel into iron metallurgy. The problem of using something more than driblets of coal at the forges where pig iron was made into bars and rods remained to be solved. Until it was solved, the iron-works generally had to be grouped about the forests rather than about the expanding coal-mines. As the ironmasters required charcoal in large quantities for converting pig into bar iron, they may have felt that they might as well use it also in their blast-furnaces.

Some seventy years later, about 1784, Henry Cort (1740–1800) invented the so-called puddling process, in which the evolved heat of coal fuel was transmitted by reverberation to make pig iron into bar iron. This invention, combined with Cort's new method of finishing iron by passing it through grooved rolls, ensured the triumph of coal in iron metallurgy. Puddling made it possible to eliminate the deleterious sulphur from the iron.

Some 200 years elapsed, then, between the time at which the technical problem of substituting coal for wood fuel was first raised in an acute form and the actual effective union of coal and iron. It seems to have been, above all, the advent of a coal-burning economy in Britain, beginning at the turn of the sixteenth and seventeenth centuries, which brought about the union.[1] The need that arose about 1600 for substituting coal, cheap near the mines and anywhere near navigable water, for wood, cheap only at great distances from the principal markets for iron, provided an unprecedented stimulus for technical inventions of new kinds. The fact that this need was felt at the same time in a host of other industrial processes focused the attention of inventors on the various problems of substituting coal for wood. In the long run, it provided inventors with a wide range of experience on which they could draw for the knowledge they needed to solve the especially difficult and complicated problems presented by the substitution of coal for charcoal in iron-metallurgy.

IV. COAL MINING AND TRANSPORT

The need for digging and transporting coal in far greater quantities than ever before, caused by the expansion in demand at the juncture of the sixteenth and seventeenth centuries, made acute two other technical problems, whose eventual solution precipitated the industrial revolution 200 years afterwards. One was the drainage of mines at a considerable depth. Flooded pits had plagued the miners of central Europe even before the first Elizabethan age. During the late fifteenth and early sixteenth centuries there was a great increase in the demand for copper, and for the silver which was being obtained for the first time from argentiferous copper ores. This led to more intensive mining in central Europe, and ingenious engines for raising water were devised, notably in Hungary. Some of these engines had come into fairly common use in Germany and the adjacent countries to the east and south in the time of Agricola, whose celebrated posthumous treatise on mining and metallurgy, *De re metallica*, appeared in 1556 (vol II, p 13). The machinery for drainage, like the machinery that moved the most powerful bellows and the heaviest hammers in the metallurgical works, and like that which raised salt water from the brine-springs at the principal salt works, was driven by horses or by the force of moving or falling water.

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[1] To some extent, however, the advent in seventeenth-century Britain of a coal-burning economy might be represented as delaying the solution of the problems of smelting iron ore with coal. The adoption of coal in so many other industries reduced the pressure on the English forests for wood fuel, and perhaps encouraged ironmasters to persist in the use of charcoal.

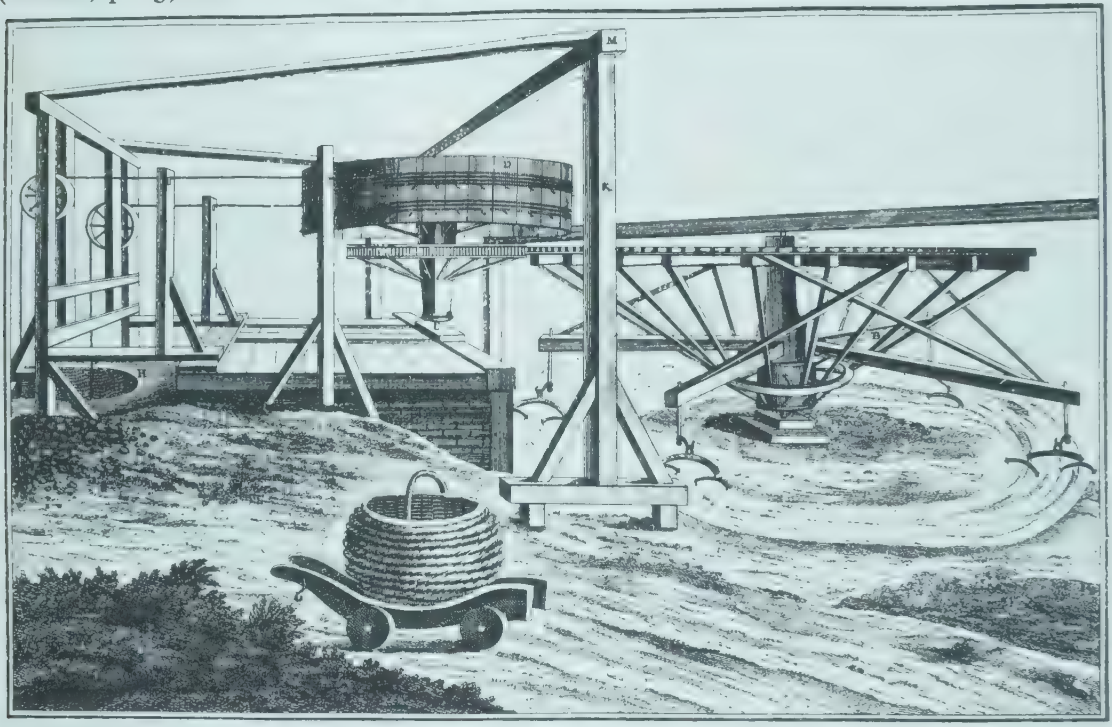

FIGURE 45—*Horse-whim haulage machine used at Newcastle-upon-Tyne. 1773.*

Until after the Reformation Britain was backward compared with the leading continental countries in the use of such power-driven machines. During the last half of the sixteenth century Englishmen travelled abroad, especially in Germany, in search of technical knowledge that could be used in mining as well as in metallurgy. Foreign mining-experts from central Europe came to Britain to instruct the English and the Scots (p 63). Models of the most ingenious engines known hitherto in Hungary, Bohemia, Saxony, and the Harz were set up for inspection in some mining centres in Great Britain, notably at Wollaton on the outskirts of Nottingham.

By the end of the sixteenth century it was becoming plain that the early sources of power for driving machinery—wind, water, and animals—would prove inadequate to meet the special problems of draining flooded coal-pits which the unprecedented growth of coal-mining in England presented. Silver-bearing ores owed their value mainly to their scarcity. In connexion with these ores, the new horse- and water-driven engines, introduced in mining and especially in metallurgy at the beginning of the sixteenth century in central Europe, proved economical for a time, partly because the silver and copper fetched good prices, until the inflow of American silver during the second half of the sixteenth century depressed the markets. Coal, on the other hand, owed its new-found value mainly to its abundance. Mine-owners in Britain were staggered, as their continental predecessors had never been, by the cost of drainage even when they copied the most advanced continental methods. It was difficult to produce coal for long at a profit when it was necessary to maintain many squads of horses to drive the engines (figure 45), or, in lieu of horses, to divert streams and even rivers from their courses and dam up water to drive such engines. It was more difficult in mining than in metallurgy to make this substitution, because the water-power for driving the hammers at metallurgical works could be concentrated, as the water-power for driving drainage-machinery at coal-mines could not, for a fairly long stretch of time at a single place. In short, the costs of the older sources of power for driving machinery were rendered almost prohibitively high in connexion with such a product as coal, widely considered so objectionable and vile that the greatest English poet made his characters shun Master Seacoal[1] whenever he appeared on the stage. Consequently, the pressure that a coal-economy exercised for the discovery of a new source of power capable of cheapening the costs of machinery was unprecedented.

At their wits' end to deal successfully with the problems of flooded coal-mines, mining-experts began to turn to the knowledge which had long existed that power might be generated by a jet of steam. At the very beginning of the seventeenth century in England, and to a lesser extent on the continent, some persons set about trying to apply this force of steam to solve the new difficulties of draining coal-mines. Attempt after attempt was made throughout the country. As one colliery expert remarked almost a hundred years after the treatises of Sturtevant and Rovenzon were printed, and after experiments with steam were tried, whoever discovered a practical, workable steam-engine to help the mine-owners to drain their pits was sure to be rewarded so handsomely that he could set up in London with his coach and six [17].

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[1] 'Much Ado about Nothing.'

He had hardly written those words when primitive steam-engines were in fact installed in collieries, first in Staffordshire about 1712. They spread thence quickly to other parts of the British Isles, and to the continent. It was, however, not until seventy-five years later—not until the widespread application of Watt's invention of a rotary engine in the 1780s—that steam-power began to come into general use for driving machinery in manufactures. The preliminary experiments at the beginning of the seventeenth century brought about by the early, precocious expansion of the British coal industry, were no less essential a preparation for the invention of the steam-engine than for the union of iron and coal.

Similar problems of meeting high costs with a commodity that fetched such a small price as coal created a need for cheaper means of transport, especially over land. The relative advantages of water- over land-transport for so bulky and cumbersome a commodity as coal were even greater at the beginning of the seventeenth century than at the beginning of the twentieth. But with the exhaustion of the most favourably situated surface-seams that accompanied the fuller exploitation of coal-mines, it was necessary to mine large quantities of coal some distance from harbours or navigable rivers. This led to the perfection of a new means of transport over land.

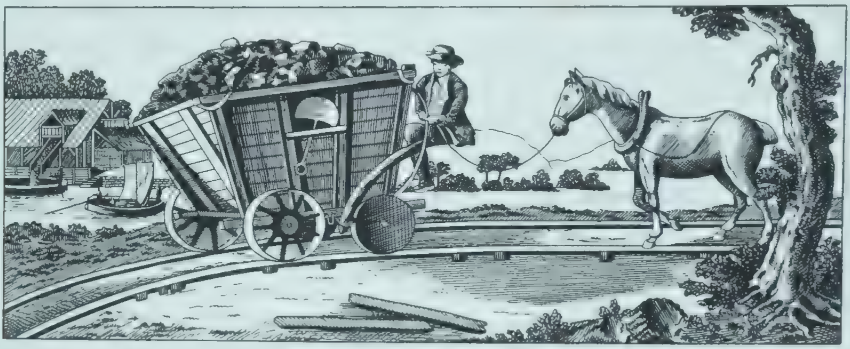

FIGURE 46—*Horse-tram used at Newcastle-upon-Tyne. 1773.*

Between 1598 and 1606 wooden rails were joined to the ground and a semi-permanent way was thus created from collieries at Wollaton to the river Trent, and from collieries at Broseley to the Severn [18]. These rails were apparently laid along an inclined way so that wagons loaded with coal at the pit's mouth could be run along them to the wharves where the river ships loaded, the empty wagons being hauled back along the rails by horses.

The idea of the railway may have been derived by Elizabethan Englishmen from Germany where, at the time of the silver- and copper-mining boom of the early sixteenth century, blocks of wood had been laid for short distances of some metres at certain metal-mines in central Europe, and wagons with a pin underneath to keep the wheels from slipping off the track had been pushed to the furnaces by hand. But the use of what were called tilting-rails was an English invention. It was prompted by the novel need for moving certain dirty, cheap commodities in ever-increasing quantities. By the eighteenth century, horse-drawn railways were used for hauling coal to the rivers and harbours in all the principal coalfields in Britain (figure 46). At about this time an attempt was made to introduce such rails into Germany, and it is significant that in the Ruhr at the end of the eighteenth century the innovation was known as an *englischer Kohlenweg*. The railway in its modern form was an English idea, developed by long-forgotten special technicians at coal-mines, more than two centuries before steam-engines—likewise invented because of the pressure of coal-mining problems—were introduced to haul the wagons.

V. COAL AND THE DEVELOPMENT OF TECHNOLOGY

As previously mentioned, the rise of the British coal industry at the end of Elizabeth I's reign was of capital importance in raising problems whose solution led almost inevitably to the industrial revolution. The wholesale use of coal in iron metallurgy made possible the utilization of iron and eventually of steel for machinery, and for construction-work of many kinds. Steam-driven machinery, when applied to manufacture as well as to mining, led men a long way in the direction of the machine-economy characteristic of the world in which we live. Traction on rails, when combined with the steam-engine for haulage, transformed both the movement of freight and the movement of travellers over ground. The entire system of canals, developed in England during the second half of the eighteenth century, was planned and executed primarily to permit the transport of coal at a low cost to those parts of the country where it was most needed. While the potential heat stored up in coal could be carried in a more concentrated form than that stored in firewood and other combustible materials, coal was a very bulky material, nasty as well as expensive to handle without the power-driven machinery whose development coal was stimulating. So, as Mantoux wrote fifty years ago: 'The more we study the history of communications by water in England, the more do we realize how closely it was interwoven with the history of coal' [19].

Before the end of the eighteenth century, therefore, coal had entered into the blood-stream of economic life, as a force that was helping to move technological endeavour in novel directions unknown to the technicians of any earlier society.

While the coal industry of Britain dwarfed that of other countries during the seventeenth and eighteenth centuries, coal was by no means without its technological influence at this time in continental Europe. As early as 1638 a tract on canal-building by a man named Lamberville appeared in France [20]. In it the author advocated the construction of canals partly as a means of carrying fuel, particularly coal, from one part of France to another. By the beginning of the eighteenth century the advantages of coal as a fuel, in spite of its nauseous properties, had begun to impress men in all the leading European countries, and overseas in North America. Technological development, in imitation of England —*à l'imitation de l'Angleterre*—became a kind of watchword among the French, and gradually among the Germans, the Dutch, the Belgians, and, finally, the Spaniards. Foreigners—at first especially Frenchmen—paid visits to Britain for the purpose of studying the new technology, which they realized was based in no small measure upon the precocious exploitation of the British coal-mines. Ticquet, whose observations remain in manuscript [21], anticipated to some extent the more celebrated work of Jars, a French government official who travelled all over Europe and published in the 1760s his *Voyages métallurgiques*. It was apparently not until the first decade of the eighteenth century, 100 years after the invention had been made in England, that French glass-manufacturers adopted coal-burning furnaces. In the meantime, the English seem to have greatly improved these furnaces, so that the coal fires were less damaging to the materials than they had been in the beginning. The result had been a new kind of glass, of British invention, called flint-glass (p 221). The French, with their predilection for quality, had been developing the aesthetic aspect of technology, and in glass-making as in other industries a bridge was thrown across the Channel by the attention that British inventors were beginning to pay to substance and appearance in the commodities they turned out in coal fires. During the eighteenth century, and especially during its second half, the continental peoples adopted one English technical process after another. By the end of the century they had in many cases begun to improve upon them. Had it not been for the French Revolution and the Napoleonic wars, it is conceivable that they might at this time have forged ahead of Britain even in the technological development that owed its strength to the use of coal fuel.

When the nineteenth century opened, coal had become a great driving-force in technological development throughout western Europe and overseas in North America. It was at about the close of the eighteenth century and the beginning of the nineteenth that scientific thinking began to concern itself for the first time with problems arising out of the treatment of coal and the saving of fuel. Once science had supplied general principles, the opportunities for technological advance in the mining, the transport, and the treatment of coal—as well as in the saving of fuel—multiplied rapidly.

During the first sixty years or so of the nineteenth century, Britain retained the lead in the development and exploitation of coal resources that she had gained much earlier. With the practical application of the theories of free trade derived from Adam Smith, an immense new market was opened to British coal during the twenties and thirties of the nineteenth century. Exports multiplied fifty-fold, and more, in sixty years. Other countries of Europe were obtaining from England the fuel that their own mines were sluggish in supplying. Meanwhile, Europe and to some extent the rest of the world were overtaking Britain in the development of their own coal-mines and of technical inventions stimulated by the expanding mining industry.

In the 1860s, Jevons, in his book 'The Coal Question', stated clearly that coal was the great resource on which industrial civilization had been reared. He saw that the supremacy of Britain in industry and technology had been based on coal, and that, as a result of the limitations of the natural coal resources of the British Isles, this supremacy was bound to diminish and eventually to disappear. What he failed to recognize was that the world was entering an age in which the resources of scientific discovery would be able to create new sources of power for technological development, alternative to the coal resources. The last century has not only been a period in which British supremacy in connexion with the mining and the use of coal has been lost: it has also been a period in which the place of coal in industrial civilization has steadily diminished in importance.

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[8] NEF, J. U. See ref. [5], Vol. 1, pp. 29–30, 123–30. (In saying 'five times as much', I have allowed not only for the coal of continental Europe, but for that of China and North America in the later seventeenth century.)
[9] *Idem. Econ. Hist. Rev.*, **7**, 180, 1937.
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An Accurate Map of the County of
NORTHUMBERLAND,
Laid down from the best Authorities
and Divided into its
WARDS,
Illustrated with Historical Extracts, relative to
Trade and Manufactures;
Describing also the Church Livings &c.
with several other Improvements.
By Eman! Bowen
Geographer to His late Majesty
Coldstream
BARONY OF Learmouth
WARK
Tweed

Miners and seamen, with a collier in the background. From a map of c 1760.

4

WINDMILLS

REX WAILES

With the invention of the *wipmolen* (hollow post-mill, p 94) in the Low Countries in the fifteenth century the main types of mill were established, but it was not until the end of the sixteenth century that drawings illustrating the mechanical details of windmills first appeared. They are contained in Ramelli's work of 1588 [1] and show post- and tower-mills for grinding corn and a tower-mill using a chain of pots for raising water, though not for drainage (figures 47, 48). The drawings are a distinct advance over the fanciful sketches in earlier publications purporting to describe machines. Ramelli's designs are practicable and show sufficient detail to satisfy most main questions of construction and mechanism.

Yet it was not until the beginning of the eighteenth century that any specification was published complete and detailed enough to enable a windmill to be built from it. This was contained in the second edition of a work by Mathurin Jousse [2] published in 1702. The plates are poor, but in 1765 Diderot [3] quoted this section of Jousse in full and illustrated it with five fine plates (figure 49), inspired no doubt by earlier publications in Amsterdam [4]. In complete contrast to Jousse, who relied on elaborate verbal description and shows very little detail in his drawings, these Dutch books reduce description to a minimum and all details are included in the drawings (figure 59), from which numbers of mills were built throughout the country. Jousse and the authors of the Dutch books on mills (including Linperch, a Swede) were all practical men, and their books, with that of Ramelli and archaic survivals of mills to the present day, enable us to follow the development of windmill construction and mechanism in detail.

The first mills were crude affairs, driving a single pair of stones (vol II, pp 623–8). Some had their substructures sunk in the earth of an artificial mound and were called sunk post-mills (figure 50). Examples have been recorded in the U.S.S.R., in Lancashire, and in Long Island, U.S.A., and remains have been excavated from time to time in England [5]. Probably the crudest post-mills still extant are the variety known in west Brittany as *chandeliers*, of which a handful remain, while a few survive in the islands of the Baltic, in north Spain, and in the Canary Islands. The post is embedded in a solid masonry base, and the Breton mills are so small that the miller can tend the single pair of stones only with the door open [6].

By the sixteenth century, post-mills were being built to drive two pairs of stones placed fore-and-aft in the mill, and a few of that period still survive; before that time a single pair of stones only was driven, placed in the breast of the mill.

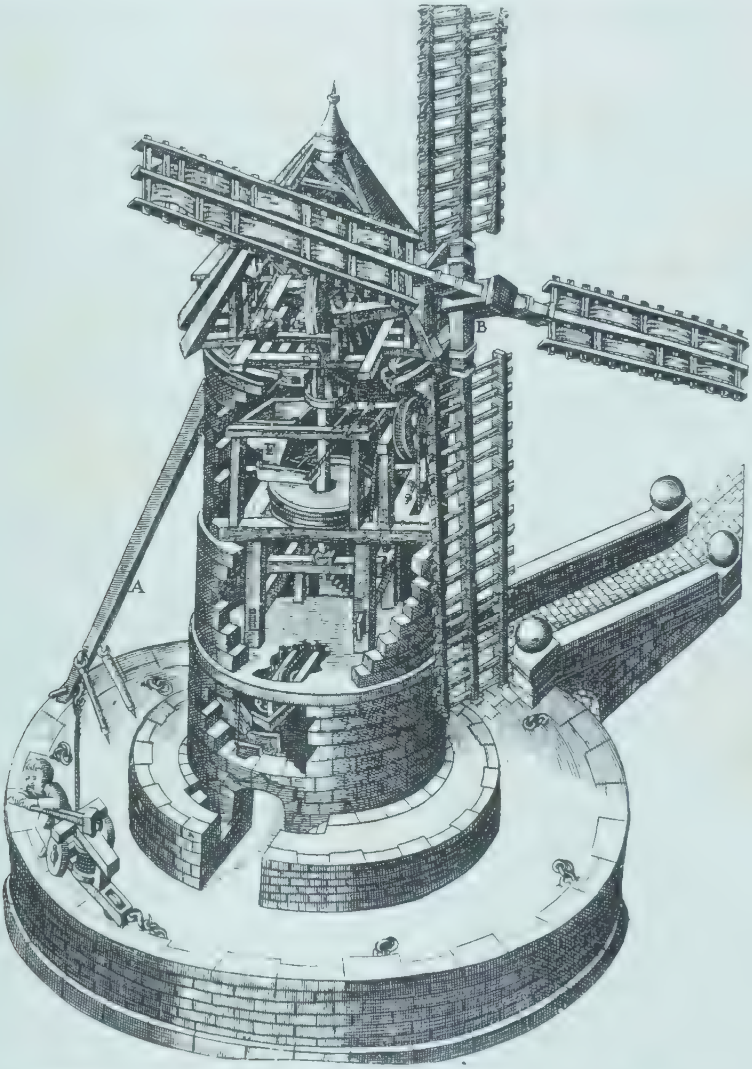

FIGURE 47—*Corn-grinding tower-mill, from Ramelli (1588). Note the threading of the sail-cloth between the sail-bars, the rollers centring and supporting the cap, and the portable winch for hauling round the tail-pole.*

The weight of the mill is taken by the upright post which is placed somewhat in advance of the centre-line of the mill and rests on two horizontal intersecting cross-trees supported at their ends by brick or stone piers (plate 5 A). The weight is transferred to the outer ends of the cross-trees, and hence the piers, by diagonal struts or quarter-bars. In England these struts were single, but on the continent they were invariably doubled; that this was so from the earliest times can be seen from contemporary manuscripts of English and continental origin. In some cases, as in Picardy, post-mills were provided with four cross-trees and no fewer than sixteen quarter-bars [7], but in England no more than three cross-trees and six quarter-bars were provided, and even that number only seldom.

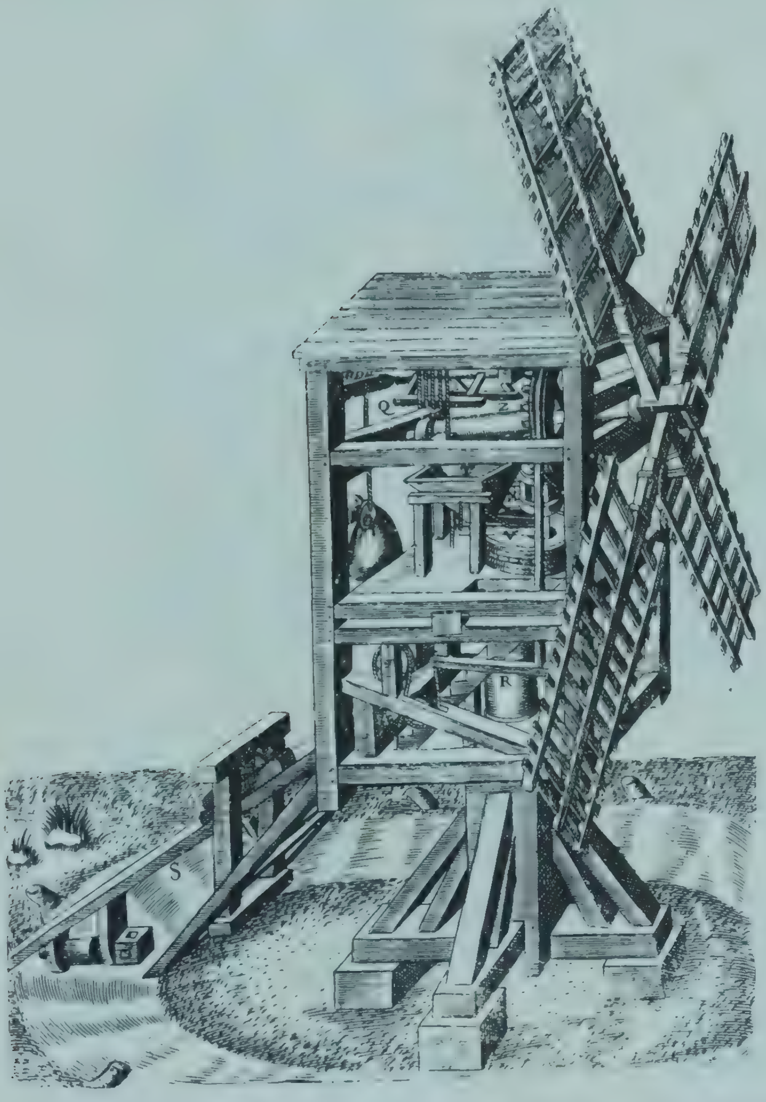

FIGURE 48—*Corn-grinding post-mill, from Ramelli (1588). The tail-pole has a winch attached and the quarter-bars are doubled as is usual on the continent of Europe.*

Very unusual substructures were to be seen in Russia, consisting of an almost solid mass of unsawn timbers (figure 55).

On top of the post of a post-mill rests the horizontal crown-tree spanning the whole width of the mill-body (plate 4 A), whose frame is based upon it. An early method of framing was to attach to each end of the crown-tree vertical struts, which extended upwards to the level of the eaves of the roof and downwards to the level of the first floor of the mill; these struts carried horizontal timbers terminating at the corner-posts of the body. In the method of construction seen in most surviving post-mills, however, two heavy horizontal side-girts (French *sommiers*) are supported by the ends of the crown-tree and in turn carry the corner-posts at their ends. The heavy breast-beam across the front of the mill at the level of the eaves and taking the weight of the sails is supported at its ends by the front corner-posts and at the centre by a prick-post. Just below the

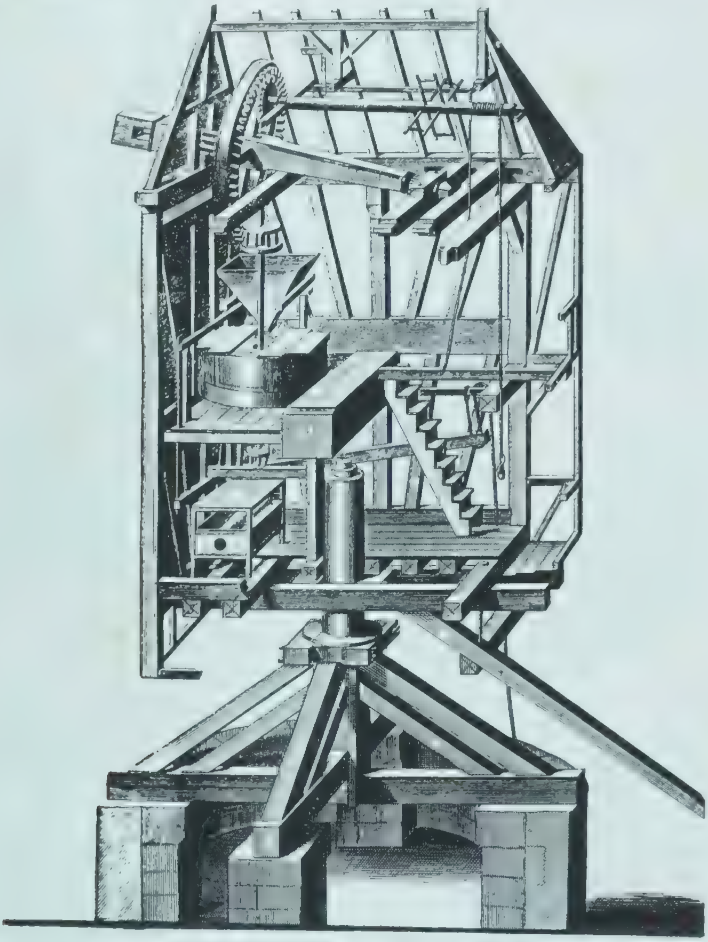

FIGURE 49—*Post-mill as described by Jousse (1702). Note the sack-hoist (in the roof) and bolter* (bottom left).

first floor of the mill are two heavy parallel timbers called sheers, running fore-and-aft the full length of the mill on either side of the post. At their ends they support the horizontal transverse timbers, at floor level, joining the lower ends of the front corner-posts carrying the prick-post. Immediately fore-and-aft of the main post two spacers were fitted and with the sheers formed a vertical steady bearing at this point, which prevented the mill from swaying about on top of the post. An additional framed bearing or collar next below the sheers was often used to form a horizontal bearing for the same purpose.

The subsidiary framing of the mill was carried out in accordance with local tradition, vertical members suitably cross-braced being employed in England and diagonal members on the continent, but local variations are numerous. In Flanders, mills dating from the Spanish occupation can be distinguished by such details [8]. Horizontal weatherboarding was favoured as a cover for the framing in England (figure 51), but shingles were used in France and vertical boarding was preferred elsewhere. In England the boarding was tarred or painted white, and in parts of the Netherlands fancy designs in various colours were, and often are, painted on the vertical boarding; elsewhere the timber was left untreated.

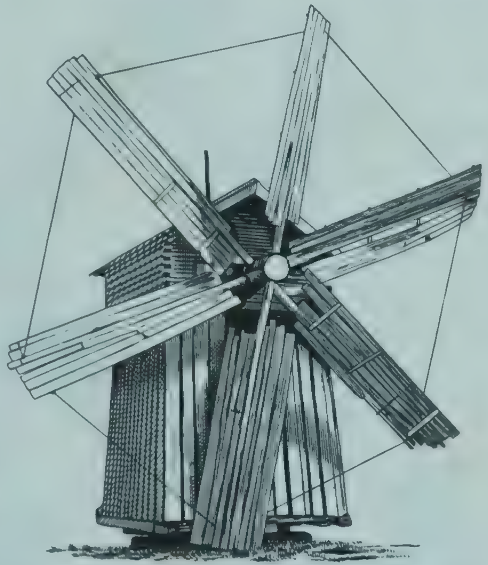

FIGURE 50—*Russian sunk post-mill with buried substructure, and six boarded sails.*

The early post-mills had straight-pitched roofs, but subsequently curved roofs in England, and ogee and mansard roofs on the continent, accommodated the more massive gearing inside. Bodies were at first small, but as mills were built with larger sails the bodies also were made larger, and some of the smaller mills were extended a foot or two at the rear to help to balance the heavier sails, to accommodate an additional pair of stones in the tail, and to provide more storage space.

The substructure in England was in later times frequently enclosed by a round-house, which served the double purpose of protecting the substructure and providing additional space for storage. In eastern and southern England it had no structural significance, but in the north-east and the midlands it was frequently provided on the top of its circular wall with a track on which skids or rollers ran. This arrangement prevented undue pitching in a gusty wind. On the continent the round-house seems to have been much favoured in the Low Countries but less often elsewhere. That it was a comparatively late introduction is evident from old prints; it was frequently added to mills up to quite recent times. There is at present no reliable evidence of a round-house earlier than the eighteenth century, although during and after that time a number are coeval with the mill.

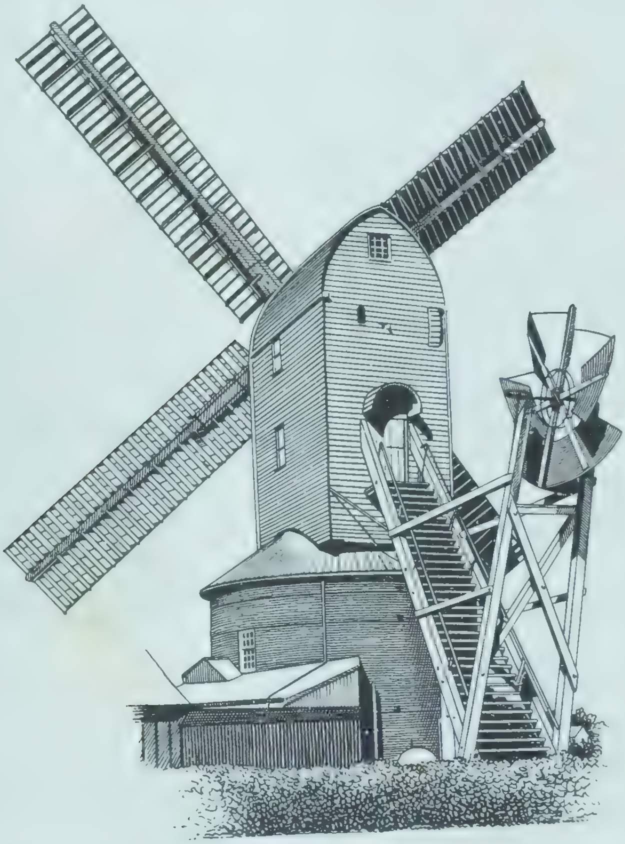

FIGURE 51—*Weatherboarded post-mill, with round-house built round the substructure. Note fantail on tail-ladder and 'patent' sails. Friston, Suffolk.*

A well designed and well built round-house was an asset and, incidentally, not seldom improved the appearance of the mill. Those built of timber often became shabby, but in England, when local stone or brick and tiles were used, the building was weatherproof and most pleasing.

The *wipmolen* (hollow post-mill), born of the necessity to drain the Low Countries by a power greater than that of the muscles of men or beasts, was a tremendous step forward, for it established the use of an indirect drive from the sails to the water-raising scoop-wheel by means of an upright shaft. This shaft had to pass down through the built-up hollow post of the movable mill-body to the fixed portion of the mill below, where the gears that drove the scoop-wheel were housed. Later this type of mill was developed for grinding corn, and in the Loire valley a distinct variety was developed known as the *cavier* [9]. Elsewhere the *wipmolen* seems to have found scant favour outside the Netherlands.

The most primitive tower-mills are today to be found round the coasts of the Mediterranean (vol II, figure 566), in the Iberian peninsula, and in Brittany. They drive a single pair of stones and are crudely but sturdily built. It is noteworthy that the earliest illustration of a tower-mill (French, fifteenth century) shows one which appears to be of superior external design to those mentioned. The essentials of a tower-mill are a fixed tower and a movable cap mounted on it carrying the sails. Both local and imported materials were used to build the towers; besides being built of brick and stone, they were also of timber where it was grown or could be imported easily. Thus we find timber-built mills in England, northern Europe, the Low Countries, and the United States. The majority of surviving timber-built tower-mills in the Netherlands date from the seventeenth century to the nineteenth, when the Baltic trade was considerable [10] and the country wealthy; the lavish use of heavy timber is most marked. Timber-framed tower-mills are typically covered with horizontal weatherboarding in England, reed-thatch in the Netherlands, and wooden shingles in Flanders and the United States.

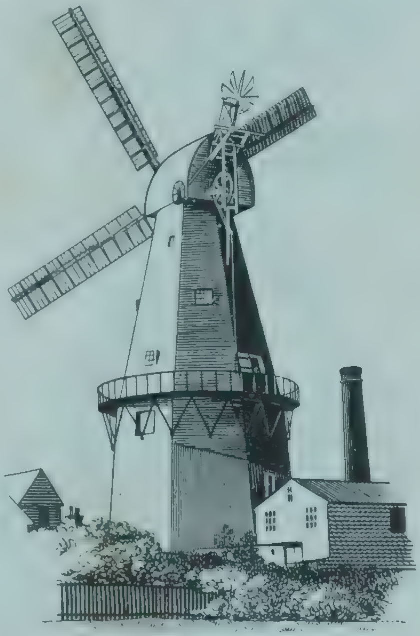

FIGURE 52—*Octagonal timber smock-mill. Note the gallery, fantail, and 'patent' sails. Cranbrook, Kent.*

In England these timber tower-mills were frequently painted white, were usually octagonal (figure 52), and were known as smock-mills from their resemblance to the old countryman's smock-frock. It is difficult to render the corners of such a weatherboarded mill weather-tight, and deterioration was much more rapid than with the reed-thatched mills of the Netherlands. Brick tower-mills in England were frequently tarred to prevent wet from penetrating the brickwork (figure 53), but this practice was not in vogue elsewhere. Round brick towers as well as the octagonal wooden ones were usually given a taper or batter from bottom to top, although this was by no means invariable. It prevented the tower becoming unduly distorted and also gave increased room at the base where it was most needed. In France and the countries of southern Europe this practice was not followed, and the walls of the towers are proportionately thicker to withstand the weight of the cap and sails. In Brittany short two-storeyed stone-built mills of a type known locally as *petit pied* or *ventru* [10] actually have an oversailing upper floor, larger in diameter by several feet than the ground floor, and walls of a thickness up to 4 ft 6 in. Some *petit pied* mills are of great age, one at Paclais (near Savenay, Loire-Inférieure) dating from 1340, though it has been largely rebuilt (figure 54). In south-west Spain towers with equally thick walls of rubble were built round two parallel arches which supported the upper floor.

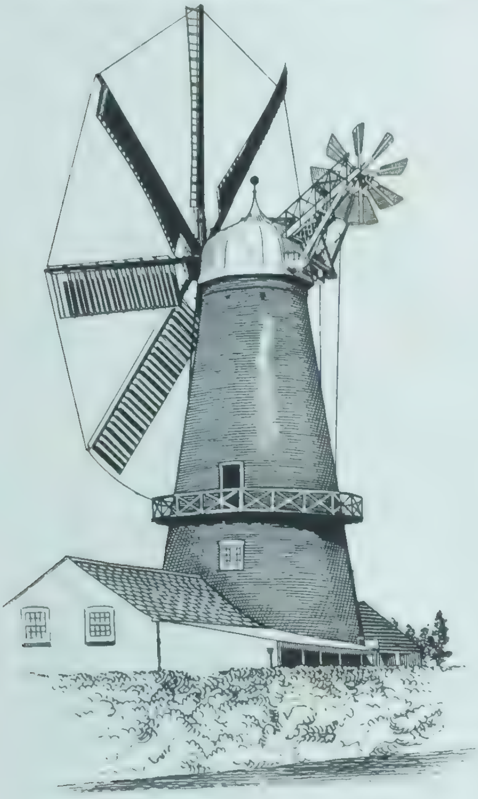

FIGURE 53—*Brick tower-mill, with gallery, fantail, and eight sails, at Heckington, Lincolnshire.*

As the tower-mill became higher it proved necessary to build a stage round it, so that the sails could be reached without a ladder (figures 52, 53, 57) and the length of tail-poles (in the Netherlands) kept within bounds. Most stages were of timber, but a few in England were of iron, where galleries were also sometimes constructed round the caps. While the stages are attractive and useful, the galleries spoil both the appearance and the air-flow behind the sails.

On the top of all towers is a track or curb on which the cap turns. In primitive mills this was and is of unfaced wood; the cap slides round on it on wood skids, being centred by similar skids bearing on the side of the curb. Later types of these 'dead curbs' were faced with iron on top and side, and iron blocks ran on them. Ramelli (figure 47) shows an independent ring of rollers inserted between the cap and the curb, and rollers fixed to the cap centring it, while the Dutch mill-books show similar roller-rings in use in *paltrok* mills (figure 59 and p 106). These are known as 'shot curbs'. In the Netherlands fairly large wooden rollers (about 7 inches in diameter by 7 inches in face) were used, while in England cast iron rollers of about half this size were normal practice. In England, however, the 'shot curb' was not very popular, a modified form, the 'live curb', being preferred. In this type, iron rollers were fixed to the cap itself and ran on the track on the curb. The later curbs in England were of iron, cast in segments and held to the tower with anchor bolts.

The caps of tower-mills are often as distinctive of the region to which they belong as are the head-dresses of the countrywomen in Brittany or the Netherlands. Thus in south-eastern England the typical cap resembles the curved roof of an English post-mill (figure 52); in Norfolk it is of a neat boat-shape; in the north-west it is of a much larger boat-shape, and in the north-east and midlands an ogee, a shape also found in Denmark, Sweden, and Germany (figure 53). There are similar variations in other parts of Europe, the conical cap being favoured in France and the south generally.

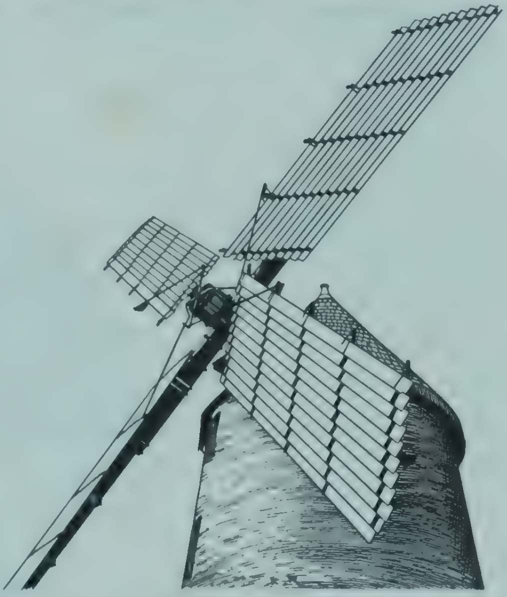
FIGURE 54—*Raised* petit pied *mill with Berton sails (open) at Savenay, Loire-Inférieure, France.*

The post-mill was turned into the eye of the wind manually, by pushing against a long tail-pole, which was attached to the body of the mill and extended downwards at an angle, passing through the ladder at the back of the mill (figures 49, 55). In England the ladder normally rested on the ground and acted as a back stay, restraining the mill from pitching when at work; it therefore had to be raised off the ground before the mill could be turned. This was done by a lever pivoted on the tail-pole, one end of which was connected by chains to the bottom of the ladder. By pulling on the other end of the lever the ladder could be raised, and when this was done the lever was held in place parallel to the tail-pole by an iron pin; the mill could then be pushed round with the tail-pole. An alternative method was to fix a cart-wheel to the tail-pole, leaving the ladder permanently clear of the ground (figure 48). In Flanders two hinged struts on the tail-pole were used to steady the mill, while in Prussia wooden poles were wedged between the rear corner-posts and the ground for the same purpose, the ladder of the continental mill not resting on the ground.

If the mill is well balanced and well maintained it is not difficult to push round by hand, but mechanical aids were not despised. The earliest was a portable ungeared winch, which could be anchored to one of a number of posts set round the mill (figure 47). A chain or rope was run out from the winch to the tail-pole and wound up on the winch, thus turning the mill; later the winch was fitted to the tail-pole itself.

With the introduction of improved metallurgical techniques in the mid-eighteenth century it became possible to cast gears of iron. This opened the way to improvements in turning the mill. Hand-winches were geared, and in 1745 Edmund Lee patented the automatic fantail [11] (figure 51) (erroneously attributed to Andrew Meikle). This device consists of a jack or fly at first mounted on a carriage at the end of the tail-pole which, through iron gears and shafts giving a very considerable reduction in speed, drives two road-wheels running on a track set round the mill, a subsidiary track being provided for smaller wheels supporting the base of the ladder. As long as the mill faces square into the eye of the wind the vanes of the fantail, usually six or eight, present their edges to the wind, but when the wind changes direction it strikes the vanes at an angle and turns them, thus turning the mill until it faces squarely into the wind once more.

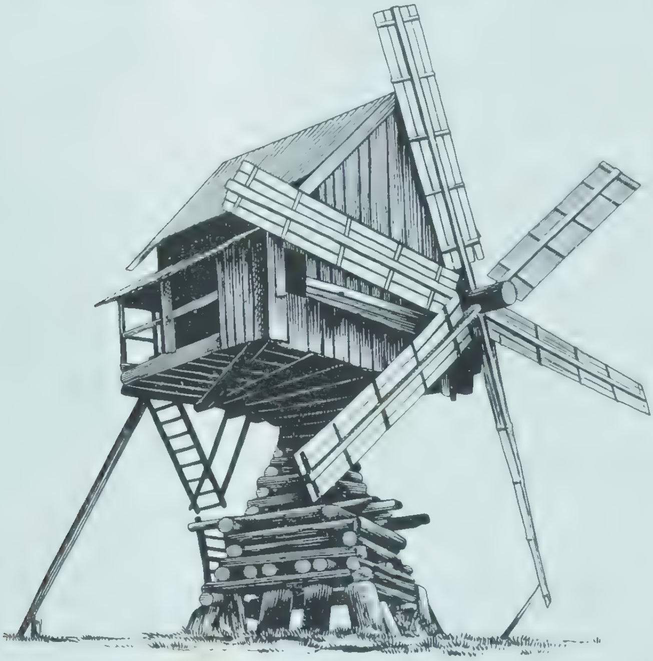

FIGURE 55—*Russian post-mill on massive timber substructure. The wind-shaft, carrying six boarded sails, is mounted in the lower right-hand corner of the body, and drives upward.*

It was found that when the fantail was mounted on the end of the tail-pole it would sometimes act as a weather-vane in strong gusts, so in East Anglia the tail-pole was usually cut short and the fan-carriage mounted on the end of the ladder. A few post-mills had fantails mounted on their roofs, driving down either to wheels on the bottom of the ladder, or to a worm-wheel mounted on the post just below the bottom floor of the mill.

The tail-pole was also used to 'wind' the caps of tower-mills (figures 52, 53). In France, and in southern Europe generally, it is fixed to the inside of the cap without external bracing, and this method is shown in the early illuminated manuscripts. In England, the Netherlands, and northern Europe, however, it is customary for external bracing to be used.[1] Movable ungeared winches and geared winches fixed to the tail-pole were used, and the winch was also transferred to the cap itself, operated either from inside as in the Netherlands, or from the ground by endless chain and gearing engaging with a rack fixed to the curb on the top of the mill-tower as in England. From the latter method the fantail drive was but a step; however, the fantail did not spread from England to Denmark and north-western Europe until about a century after its invention, and is not generally to be met with on the continent south of the two northern provinces of the Netherlands. Its use relieves the miller of much hard work and enables him to leave the mill unattended when not working. Its one disadvantage is the risk of 'tail-winding' if a thunderstorm passes closely over the mill, for it is not an easy matter to turn the cap quickly by hand when any form of reduction-gearing is used.

The early sails [12] were flat frameworks, inclined at an angle, over which cloths were spread or else laced in and out of the bars of the sail-frames (figures 47, 48). Very primitive forms of sail are still to be found in Brittany built of unsawn timber, in which the absence of a hem-lath, connecting the bars at their outer ends, makes the sail appear like a comb. Another primitive type found in Sweden, and until recently in Germany, had removable boards, instead of sail-cloths, fitted to sail-frames, while in the U.S.S.R. sails were made of a number of light wooden boards running the full length of the sail (figures 50, 55). The Dutch mill-books yield the earliest information on the twist or 'weather' that is a feature of the cloth-covered sails we know, with the cloths spread over the surface of the sail and not laced in and out of the bars.

The sail-cloths are attached to rings running along a bar on the inner end of the sail. When the cloths are not in use they are furled to one side, wound up like a rope, and tied to a sail-bar near the outer end of the sail. To set the cloths each sail is brought round to the bottom position in turn, the cloth is unwound, and looped cords on the selvedge are slipped over wooden cleats on the leading edge of the sail-frame. The cloth is then pulled across the sail-frame by means of four cords, called pointing-lines, attached to the selvedge. By them the cloth can be set to 'sword-point', 'dagger-point', 'first reef', and 'full sail', according to the wind and the power required.

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[1] In the Mediterranean area caps are often turned from within by means of a crowbar and a series of holes round the curb.

The sail-frames consist of horizontal bars mortised into a main timber backbone called a whip and connected at their outer ends by hem-laths. In primitive sails there is sail-area on both sides of the whip. In England, the Low Countries, and parts of northern Europe the single-sided sail was developed, having sail-area on the trailing side of the whip only and a leading-board on the leading side; in the Netherlands this design was carried to a high pitch of efficiency. Near the sea in the Iberian peninsula, and in the eastern Mediterranean, triangular jib-sails are used. No sail-frame is provided, the cloths being wrapped round radial poles; the required amount of sail is unwound and braced to the tip of the next pole. A bowsprit extends forwards from the centre and the tips of the poles themselves are braced to it, any number of sails from eight to sixteen being used.

John Smeaton (1724–92) first investigated scientifically the design of windmill sails, experimenting with a whirling table and presenting his conclusions to the Royal Society in 1759 [13]. His recommendations on angles of weather were no doubt followed by millwrights to some extent, but, in England and the Netherlands at least, most country millwrights followed their own traditional practice, attained and modified empirically.

The difficulty of setting and shortening sail-cloths in uncertain weather led to the invention of the spring-sail in England in 1772 by Andrew Meikle. He set a number of hinged shutters in the sail-frame, connecting them together by a bar and controlling the movement of the bar by a spring, the tension of which could be varied by means of an adjusting mechanism at the tip of the sail. The spring was adjusted to permit a certain wind-pressure to be used; when this pressure was exceeded it overcame the resistance of the spring, and the shutters opened and 'spilled the wind'. Once the spring adjustment had been made individually, the action of each sail was automatic and the sails were self-regulating; but as the shuttered sail did not provide so much power as the cloth-covered sail, to whose 'weather' it could only approximate, it was quite usual to drive a mill with two spring-sails and two common sails to make the best of both methods.

In 1789 Stephen Hooper of Margate, Kent, invented his roller-reefing sail. In place of the shutters of the spring-sail small roller-blinds were fitted, and all the operating rods of all the sails were connected by cranks and levers to a spider-coupling at the centre. A hole was bored through the wind-shaft carrying the sails and a rod passed through it, connected at the front to the spider-coupling and at the rear to a rack and pinion and a chain-wheel around which passed an endless chain hanging down to the ground. By this means it was possible to open and close all the roller-blinds in all the sails simultaneously without stopping the mill. The inventor claimed that the blinds operated automatically while the mill was at work, but in practice this did not happen. Such sails were used in Kent, Lincolnshire, and Yorkshire.

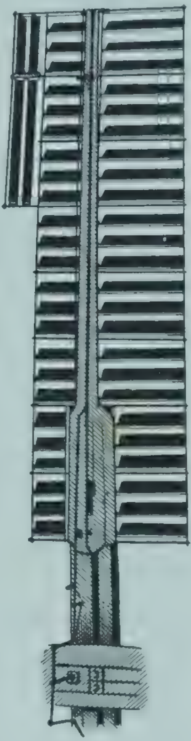

FIGURE 56—*A sail fitted with Catchpole's air-brake. This is formed by the two longitudinal shutters attached at the side of the main frame of the sail. From a post-mill at Gedding, Suffolk.*

In 1807 William Cubitt (1785–1861) combined the shutters of Meikle's spring-sail with the remote control of Hooper's roller-reefing sail, to devise what has always been called the 'patent' sail (figures 51, 52, 53). Its operation is truly automatic, the sails being controlled by hanging weights on one side of the control chain; the heavier the weight the greater the wind-pressure required to open the shutters and spill the wind. By hanging the weights on the other side of the chain the shutters can be held open. Shuttered sails may have shutters on both sides of the whip or on the trailing (or 'driving') side only. If well designed the single-shuttered sails will start more readily at low wind-velocities and some sails have been converted from double to single for this reason.

About 1860 Catchpole, a millwright of Sudbury in Suffolk, devised the first air-brake (figure 56). He fitted two longitudinal shutters on the leading edges of 'patent' sails parallel to the whip and at right-angles to the main shutters. These when closed gave additional sail-area, but when opened spoiled the air-flow and acted as a brake. The idea was used, though sparingly, in Suffolk, Lincolnshire, and Yorkshire only, but was revived in the Netherlands in the 1920s.

At about the same time a miller at Haverhill in Suffolk designed the first annular sail, of 50-ft diameter with shutters operating like those in a 'patent' sail (figure 57). Four such sails operated successfully in East Anglia and were the precursors of the American wind-pumps, of which a variety of types was produced.

In France, about 1840, the Berton sail was invented [14]. This is a cheaply built, non-automatic sail with remote control which can be operated from inside the mill while it is at work. It consists of a number of wooden slats operating like a parallel rule; when open they present an unbroken rectangular surface with a constant angle of weather and when closed nest up one behind the other. The Berton sail was widely used and is still to be found in France (figure 54).

The wind-shaft carrying the sails is set in the top of the mill-body in post-mills and in the cap in tower-mills [15]. The shaft is normally inclined upwards at an angle of between 5° and 10° so that the sails may clear the lower part of the mill, that they may be more easily balanced on the shaft about the neck-bearing immediately behind the sails, and that a thrust-bearing can be provided at the tail of the shaft. The first wind-shafts were of wood, and at the nose of the shaft mortices accommodated two heavy timber stocks at right-angles. These projected equally on each side; they were wedged in place and each carried two sails, the whips of which were bolted and clamped to them. In the Netherlands whips are dispensed with, and the sail-bars are mortised into the stocks themselves, while the primitive sails in Brittany have the ends of the whips wedged into the wind-shaft and no stocks. Rotting of the nose of the wind-shaft was a constant trouble, not overcome until cast iron shafts were introduced by John

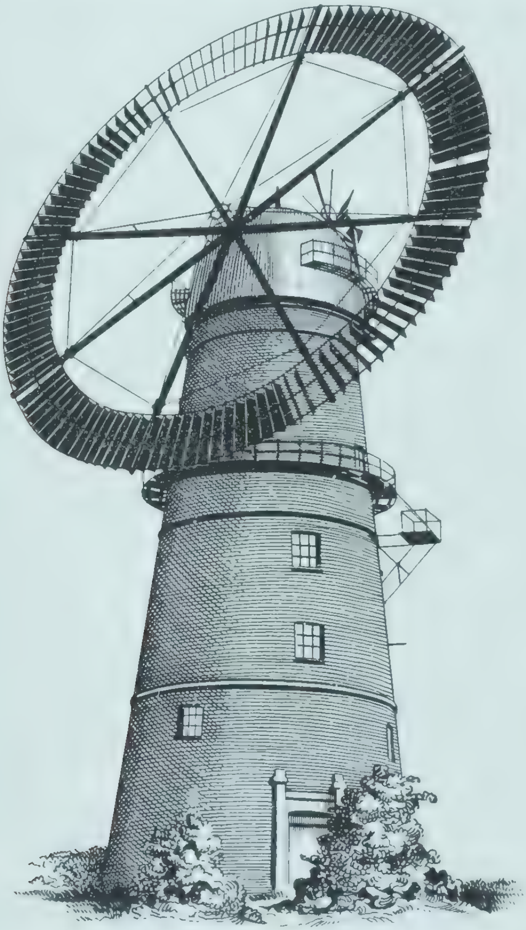

FIGURE 57—*Tower-mill with annular sail at Haverhill, Suffolk. The gallery and fantail are visible.*

Smeaton. Preferring five sails to four he devised an alternative method of mounting them on a cast iron hub with arms, known as a cross, fixed to the nose of the wind-shaft. The size of the whips was increased and they were bolted and strapped to the cross. The use of this much superior method was confined to the area roughly to the north and west of Cambridge in England and to a few examples on the continent. Elsewhere in England and Europe iron poll-ends, like two boxes at right-angles with their ends knocked out, were fitted to the wooden shafts, or iron shafts incorporating poll-ends were installed.

Since the use of eight to sixteen jib-sails has been mentioned it should also be noted that mills with six common sails (figures 50, 55) were in use in the Mediterranean area and in Russia, while in western Europe the multi-sailed mill had a vogue only in England, and then only where the cross was adopted. Six sails were most favoured, but five-sailed mills were not uncommon, and at least seven eight-sailed mills are known to have been built (figure 53).

The journals of wooden wind-shafts consist of wrought iron strips sunk flush in the timber and looking not unlike the commutator of a direct-current electric motor, but in many cases iron tail-ends as well as poll-ends have been fitted to wooden shafts. The thrust-bearing on a wooden shaft is an iron ring on the back face, and when a cast iron tail-end is fitted the thrust is taken by a small flange at the tip of the journal. The early bearings were of wood or stone and these materials are successfully used today; the neck-bearings have a circumferential contact of about one-quarter to one-third. Brass bearings came to be used with cast iron journals in England, and a neck-bearing is called a 'neck-brass' in England but a *marbre* in France. A refinement to be found in East Anglia is a self-aligning bearing housing on trunnions.

On the wind-shaft of the mill is mounted the brake-wheel (plate 4 B), so called because a contracting brake acts on its rim, and in some post-mills a similar but smaller wheel called the tail-wheel is mounted farther back on the wind-shaft. Where direct drive is employed both these wheels, which are face-gears on an inclined shaft, drive stones from above or 'overdrift' through a pinion called a stone-nut. Where indirect drive is employed the brake-wheel drives the 'wallower' (the first driven wheel in a mill), mounted on the upright shaft, and the stone-nuts are driven by the great-spur-wheel mounted lower down on the same shaft [16]. In the case of indirect drives the overdrift stones are driven by nuts mounted on 'quants', while if 'underdrift' the nuts are mounted on the 'stone spindles' which carry the runner-stone. In the U.S.S.R. some post-mills have the wind-shaft mounted low down in the bottom right-hand corner of the mill-body as viewed from the front of the sails, while the entrance to the mill-body is on the left-hand side and not at the rear. This implies a drive upwards, as in a water-mill (figure 55).

The primitive mills in Brittany have no brake and are stopped by being 'quartered', that is, turned till the sails are at 90° to the wind. Brakes are usually operated by heavy wooden levers, whose weight applies the brake which has to be hauled off. The brakes themselves are usually of wood, built up of curved sections connected with metal plates, but in England hoop iron is also used.

The first gears were 'compass-arm' wheels, two or three arms being mortised right through their wooden shafts. The teeth or cogs were crude pegs meshing with the round wooden staves of lantern pinions, which had wooden flanges top and bottom. Later the upper flange was dispensed with and pegs similar to those in the wheels were used. The bevel was not used until the advent of cast iron gears, and even so Smeaton's designs show no bevels in windmills. The compass-arm wheel weakened its shaft considerably, and at the beginning of the eighteenth century the clasp-arm wheel was introduced. Two intersecting pairs of arms form at the centre a square clasping the shaft, the wheel being centred by means of wedges. Iron brake-wheels are frequently cast in halves for ease of fitting, but iron wallowers at the top of upright shafts are in one piece (plate 5 B). Brake-wheels were also made with iron hubs and arms and wooden cants and rims. Wooden cogs were often sawn off brake-wheels and replaced with iron teeth cast in segments and bolted in their place. Iron upright shafts in tower-mills are almost always in two or more sections connected by dog-clutch couplings,[1] which provide a certain degree of self-alignment.

Great-spur-wheels are as diverse in construction as brake-wheels, while stone-nuts are sometimes made completely of wood, sometimes of iron with wooden cogs, and sometimes wholly of iron. They are disengaged from the great-spur-wheel in a number of ways. In an overdrive the top bearing of the quant is arranged so that the quant or the bearing can move sideways away from the wheel. In an underdrive several cogs of a wooden nut are made easily removable, and in the case of an iron nut a segment of the rim is sometimes detachable. More often, however, an iron nut is lifted clear of the great-spur-wheel by chains, a rack and pinion operating a ring from below, or a screw and ring.

The stone-spindle passes through a greased wooden bearing in the stationary or bed-stone and drives the upper or runner-stone, which is balanced on top of it (figure 58) [17]. It revolves on a thrust-bearing supported by a bridge-tree hinged at one end, which can be raised and lowered to adjust the gap between the stones. As speed varies the runner-stone tends to rise and fall and the bridge-tree is adjusted accordingly by a compound lever, originally operated by hand and later automatically by a centrifugal governor, the initial setting of the gap being made with a hand-operated screw. While there are many exceptions, the governors are usually driven by a belt off the upright shaft in the case of overdrift stones and off the stone-spindles in the case of underdrift ones.

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[1] A dog-clutch consists of two opposed flanges carrying projections or slots.

The stones are fed from grain contained in hoppers above their wooden casings, the grain passing to the stones down an inclined trough or 'shoe' agitated either by the quant or by an iron device known as a 'damsel', against either of which it is held by a spring. To warn the miller that the supply of grain in the hopper is low an alarm-bell is usually fitted in England, a sufficient weight of grain on a strap in the hopper restraining a bell on a string from falling against some moving part of the machinery.

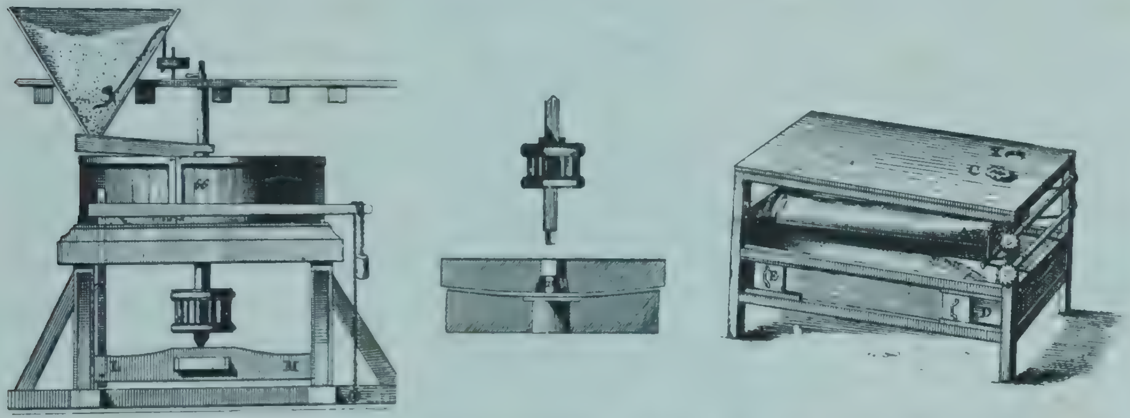

FIGURE 58—*View and partial section of underdrift millstones and gear. Note the weighted lever regulating the gap between the stones, and the hopper bell-alarm.* (Right) *Early cylindrical bolter.*

The hoppers for the stones of primitive mills were filled by hand from sacks or baskets, and before the sixteenth century there is no mention or illustration of a sack-hoist to fill storage bins above the hoppers. While hand-operated sack-hoists are still in use in France, in England power-driven hoists were the rule (plate 4 B). The drive is usually from a belt, normally slack, but tightened by raising one bearer of the hoisting-drum when required. This is effected by a cord passing down through all floors of the mill. The sack-chain, passing through double-flap trap-doors in all floors, is wound up on a drum.

In post-mills the chain-drum is in the ridge of the roof and the belt-drive is either direct from a pulley on the wind-shaft or from a gear- or friction-drive off the brake- or tail-wheel. In the case of tower-mills the belt-drive is usually derived from a countershaft driven by a bevel-wheel on the upright shaft. The common alternative is a friction-drive from below the wallower.

A number of auxiliary machines are to be found in corn-mills: of these the most common are bolters and 'wire-machines' to separate or dress the flour out of the meal. This was originally done by hand by a meal-man, and Jousse is the first to describe a bolter in a windmill (figure 58). Such machines are driven by pinions from one of the main gears of the mill, and usually the final drive is by belt. In the north of England groat-machines and 'jog-scrys' or sifters were used in the production of groats from oats roasted in kilns near by. In America corncob-crushers for extracting the grains of maize from their cobs were to be found, while in the Netherlands barley-mills to produce pearl barley are used. Oil-mills, operating drop-stamps by means of cams on the wind-shaft, were used until about 1940, and saw-mills working gang-saws by triple-throw cranks are still at work in the Netherlands. Drainage-mills drove scoop-wheels and wooden Archimedean screws (plate 20); only the former were used in England, in increasing numbers from 1588 until the introduction of steam-pumps in 1820, when within 130 years they became virtually extinct. The decline in the Netherlands has been less rapid, although one variety, the miniature skeleton *tjasker* (figure 204), in which the Archimedean screw was coupled direct to the tail of a steeply inclined wind-shaft, has already disappeared, as have the brine-pumping mills of England and New England. Some drainage-mills, using a chain of pots, survive in Spain and Aden.

The first wind-driven saw-mill was built by Cornelis Cornelisz in Holland in 1592; it was mounted on a raft which was warped round to face the wind. From this developed the *paltrok* mill (figure 59), the whole of which turns on a roll-ring running on a brick base a few feet high. In appearance it is a square smock-mill with panniers on either side, and a few post-mills in Germany have been converted into *paltroks*. In the Netherlands mills were used for every conceivable industrial purpose, especially on the Zaan, where over 900 were at work at one time before the advent of steam-power.

The horizontal mill, with sails attached radially to a vertical shaft, is still to be found in Seistan, in the north-east of Persia, where it originated and whence the idea was taken to China (vol II, figure 558). In western Europe it has never met with much success on account of its mechanical limitations, which prevent any considerable power from being developed. It has been re-invented many times between 1600 and the present day and, while it was used to some extent in south Russia, the only continuously successful variety is the Savonious S-rotor, which is outside our period.

Thus, in short, the most advanced mechanical devices were found in English windmills—the use of cast iron leading to cycloidal gearing, the use of bevel-gears, fantails, and shuttered sails—and the design of the East Anglian post-mills has never been equalled. The best-constructed tower and smock mills are to be found in the Netherlands; these cannot be rivalled elsewhere, and the Dutch always led in the design of cloth-spread sails.

The millwrights who designed and built these windmills with the aid of axe, adze and auger, pole, block and tackle, and jack were the ancestors of the mechanical engineers who started to transform the world two hundred years ago. Of those who built the early mills we know little; manorial rolls tell us something of the cost of repairs to mills, and from them we learn that, in addition to the stones, the iron portions of the mills were expensive and were correspondingly

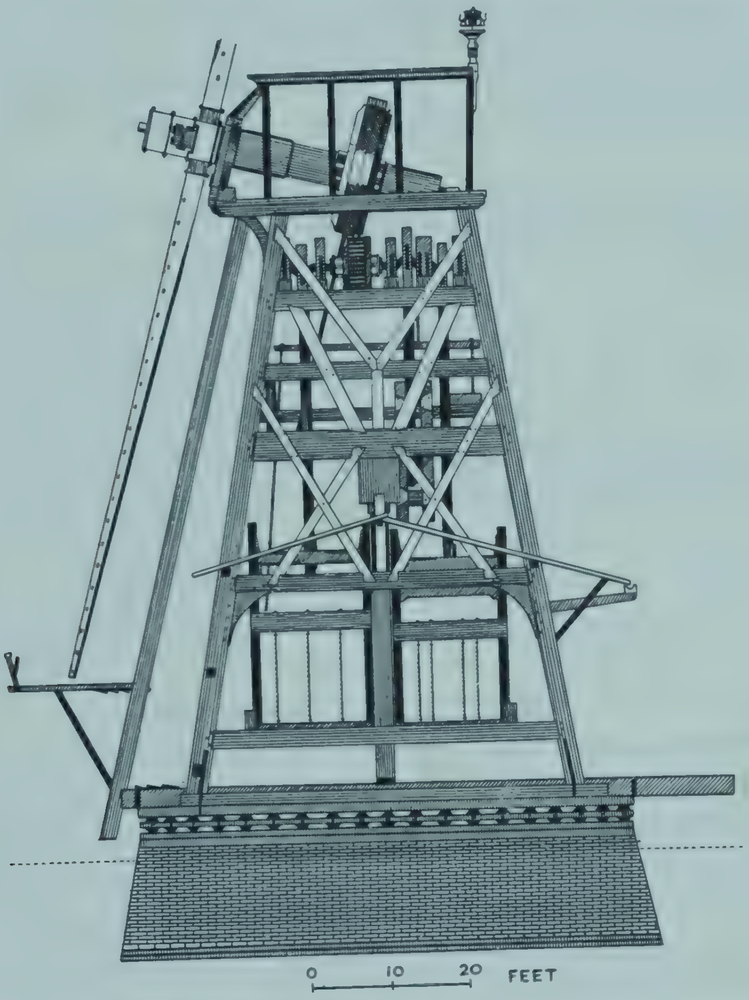

FIGURE 59—*Section of a* paltrok *saw-mill. The wind-shaft is coupled by oblique gearing to a crank-shaft, which causes two frames carrying the saws to reciprocate up and down. The timber body of the mill rotates on rollers upon a brick base.*

cared for. The parts most often mentioned are the stone-spindles and the millrynds; these are seldom found in old mill-sites, which, when excavated, have yielded mainly nails and charred or rotted timber. The nails held the weatherboards, for the framing of the mills was fastened with wooden pegs.

These millwrights were versatile carpenters, who could also if necessary frame and hang church bells and whose work can be matched in timber-framed barns, which they may well have built. Their early drawings, if any, have not survived, and it is significant that the first technical description of a windmill, already mentioned (p 89), is contained in a treatise on carpentry published in 1702.

The Dutch mill-books printed from 1728 onwards are the first to depict millwrights at work and their tools; from that time onwards we can form a clear picture of the operations involved. The broad axe and the adze were widely used, as is evident from examination of timbers in the older surviving mills. Heavy-duty lifting-jacks were also essential; but perhaps the most important element in the millwright's equipment was his rope tackle. The ropes had to be of considerable length and strength to haul up first the heavy wind-shafts, with the aid of a pole, and subsequently the sails, for the repair and renewal of which the tackle was most frequently used.

Besides building the mill and renewing and repairing the sails millwrights undertook running repairs, supplying and fitting new bearings, re-cogging gears, and sometimes dressing the stones. Dressing, however, was more often performed by the miller, his man, or an itinerant stone-dresser. The influence of a firm of millwrights could often be seen in the regional design of the mills. This could be traced along the main lines of communication radiating not only from the millwright's home town or village, but also from other centres at which his apprentices had set up as independent masters. Thus national types can be subdivided and the varieties easily recognized as regional and local.

The millwright was usually his own smith or at least employed one, but he let out his bricklaying or stone-mason's work to others, the bricks often being made or the stone quarried on a site adjacent to the mill. He had to be a man of considerable initiative, ingenuity, and resource. With the advent of steam-power it was the millwrights who built, installed, and later designed not only the engines but the machinery that they drove. This can be seen from the history of a number of famous engineering firms; the millwright can indeed justly be regarded as the ancestor of the present-day mechanical engineer.

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5

TRADESMEN'S TOOLS
c 1500–1850

R. A. SALAMAN

TOWARDS the end of the seventeenth century the artisan came to be called a tradesman, and it is under this name that we follow him into the centuries after the medieval period (vol II, ch 11).

When considering hand-tools, it will be convenient to have a rough classification of the principal types according to their uses:

Hammering: hammers, mallets, and mauls.
Cutting, splitting, and scraping: knives, wedges, adzes, axes, saws, chisels, and files.
Piercing and boring: awls, drills, and augers.
Measuring and marking: rules, squares, plumb-lines, compasses, and calipers.
Grasping and holding: pincers, vices, and brakes.
Sharpening: grindstones, whetstones, and saw-sharpening tools.

Man began making tools about half a million years ago, and it is therefore not surprising that the design of most ordinary hand-tools attained a final stage of evolution in the classical Mediterranean civilizations and has remained little changed since (figure 60). Indeed, the form of many modern tools has scarcely changed from that of their predecessors in Neolithic times. Thus, the knife of the boy scout of today is very close in form and dimensions to the predynastic flint implement of Gebel el-Arak (Egypt) dating from perhaps 3500 B.C. (vol I, p 667). Another instance is the close resemblance between the modern felling-axe of 'Yankee' pattern and the Neolithic stone axe (vol I, p 601); for both are smooth wedges with swollen sides so that the axe cleaves and cuts at the same time.

As has been shown earlier (vol I, pp 687–703) the tools and products of an Egyptian carpenter of the fourteenth century B.C. would be perfectly recognizable by his modern western counterpart. While we do not know exactly the entire kit of Roman hand-tools, it appears that workmen in even the remoter parts of romanized Europe, such as Britain, possessed most of the ordinary hand-tools except the brace, clear evidence for which does not exist in Europe earlier than the fifteenth century (figure 65 and vol II, p 653).

The form of ordinary hand-tools remained fairly static after *c* A.D. 500, but the increasing number of specialist trades that emerged during and after the Middle Ages led to an increasing differentiation in the design of some tools, which continued until the end of the nineteenth century and after.

From about 1750 attempts were made to increase the wearing properties of wooden tools. Iron plates or boxwood inserts were screwed to the soles of planes, routers, and shaves; wooden braces were plated with brass. Planes made in iron or gun-metal appeared about 1800, leading eventually to a very handsome and still sought-after iron plane of which Spiers of Ayr was one of the foremost makers [66]. The modern cast iron plane was developed in America, and it is now unusual to find a wooden bench-plane employed in a carpenter's or joiner's shop.

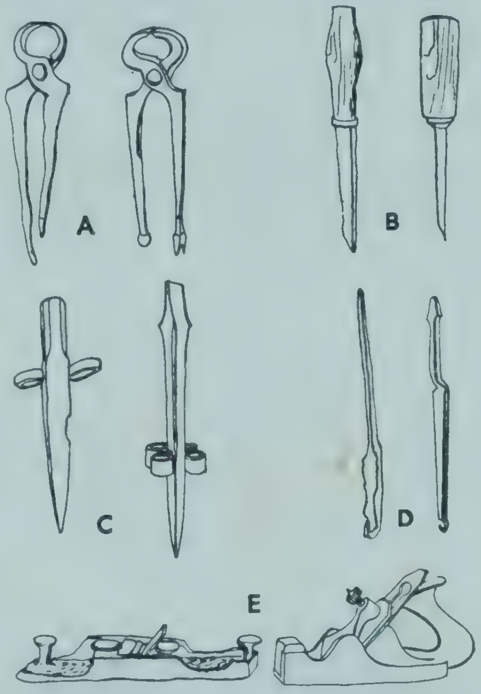

FIGURE 60—*Comparison of Roman and modern tools.* (A) *Carpenter's pincers, from a site in Germany* c *50 B.C., and modern English;* (B) *mortising chisels, from Italy* c *50 B.C., and modern English;* (C) *mower's anvils, from Silchester* c *A.D. 50, and modern French;* (D) *hooked reamers, from a German site* c *50 B.C., and modern Czechoslovakian;* (E) *carpenter's planes, from Silchester* c *A.D. 40, and modern English. Scale 1/18.*

I. THE VILLAGE WORKSHOPS

During the Middle Ages and later most villages supported a blacksmith, a carpenter-wheelwright, and a mason. The blacksmith was also a farrier; the carpenter's shop also carried out millwright's work and the management of funerals; the mason became the village builder. Thus village needs were met from within the village community.

The smithy or wheelwright's shop was sometimes part of a dwelling-house, and often set at right-angles to the road, with a yard in front in which can still be found the apparatus of cart-, wagon- and wheel-making. The scene is admirably drawn by Hennell [7]. Like the tavern, the village smithy became a meeting-place, a centre for business or friendly intercourse. Until recent times everyone was familiar with the thump of the hammer on a piece of wrought iron; with the smell of burning horn as the hot shoe was offered to the hoof; with the steady rhythm of labour in the saw-pit, and the exhilarating smell of sawn timber.

The village tradesmen developed a tradition of skill and an instinctive talent for good design. A very high level of workmanship and design was maintained. Wherever one goes, it is scarcely possible to find a poorly made cart or plough, a badly forged harrow, or shoddy work in saddlery or harness.

On looking at a dished wheel with its spokes and felloes forming a flat cone on the hub (p 124), at the assemblage of staves trussed to form the double-arch of a cask (p 130), at the intricate cross-bracing of a wagon's under-carriage, or indeed at the cutting of cloth by a tailor to fit the human body, one finds it hard to imagine how the tradesman learns to make or do these things without working-drawings or textbooks. For, so far as we know, there were few if any written sources of trade knowledge.

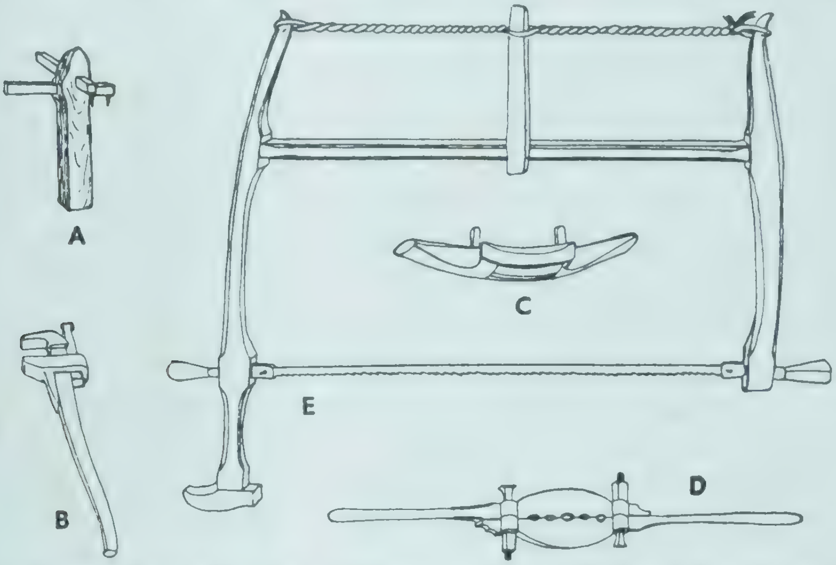

FIGURE 61—*Examples of home-made tools.* (A) *Wheelwright's gauge for scribing outlines of mortises and tenons;* (B) *adjustable wedge-spanner;* (C) *cooper's cross-shave for smoothing inside pails, etc. across the grain;* (D) *screw-die, forming thread by a pressing or rolling action rather than cutting;* (E) *bow-saw made by wheelwright for cutting felloes. Scale* A, *1/10;* B, *1/14;* C, *1/13;* D, *1/15;* E, *1/15.*

On the other hand, there existed a number of rhymes that were probably composed to help the apprentice, as was the following lesson (related by a Hertfordshire blacksmith) on how to operate the old pear-shaped blacksmith's bellows:

Up high
Down low,
Up quick
Down slow—
And that's the way to blow.

Or the sawyer's advice to the beginner in one of the most strenuous of all trades:

Strip when you're cold and live to grow old.

Or the horse-bit maker's maxim:

There's a key to every horse's mouth

—a saying that seeks to explain the infinite variety in bit-design [53].

One might imagine that something besides teaching and example existed for handing down complicated techniques; but, if so, this—like many other aspects of the workman's life and thought—is largely hidden from us.

II. HOME-MADE TOOLS

Though towns like Sheffield are known to have been centres of tool-making from medieval times,[1] most of the tools used by farmers and tradesmen in the period 1500–1700 were made by village carpenters and blacksmiths. The situation was much the same all over Europe.

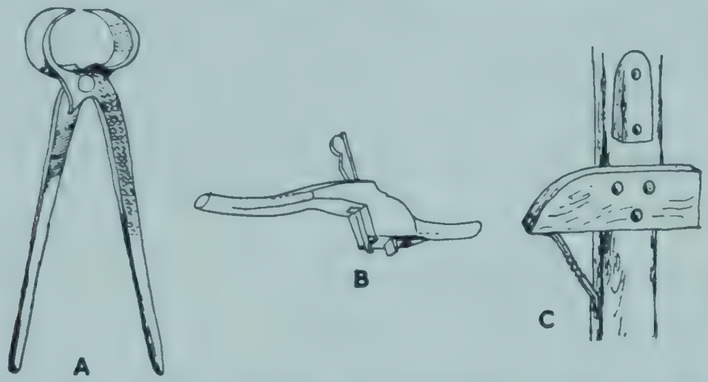

FIGURE 62—(A) *Farrier's shoeing pincers, forged from old rasps by 'Pincher Jack' (scale 1/8)*; (B) *coach-maker's pistol router, for grooving frames to take panels (scale 1/12)*; (C) *wheelwright's post tire-bender (scale 1/24).*

As late as the middle of the nineteenth century it was the rule rather than the exception for smiths to make their own tongs, anvil-tools, and even screw dies and taps. Carpenters made their own gauges, saw-frames, and often planes. Millwrights had their outsize slip-wrenches and turnscrews forged by the local smith. Coopers made their own shaves and jointers. But when the mass produced drop-forged hand-tools flooded the markets in the late nineteenth century, tradesmen soon ceased to look upon a factory-made tool as a luxury.

The plates in the eighteenth-century *Encyclopédie* of Diderot [5] show clearly that a large proportion of the hand-tools were home-made. Examples of home-made eighteenth- and nineteenth-century English tools are shown in figure 61.

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[1] Sheffield whittles (hand-knives) were familiar in Chaucer's day.

Wooden handles for chisels and augers were nearly always home-made. Some of these handles are not only a pleasure to use even today but are of great beauty. To quote Christian Barman when commenting (B.B.C., 1948) on an exhibition of old English hand-tools: 'Everybody who appreciates the qualities of materials loves wood, and here was wood formed into . . . a special kind of tactile sculpture made to be felt with the hand. . . . I remembered that old craftsmen, when they buy a new set of modern chisels, throw away the handles and carefully fit their own. These were handles . . . polished bright by a lifetime of use, and were part of their owners' lives. . . .'

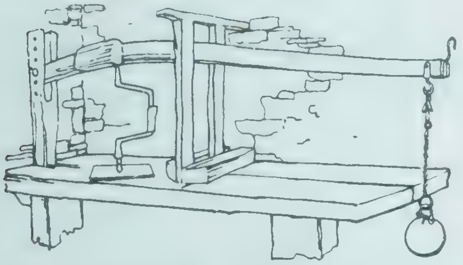
FIGURE 63—*Smith's beam-drill. The brace is turned by hand under pressure from the weighted lever. Scale 1/45.*

Before the end of the nineteenth century the factories began to produce tools, horseshoes, and general ironmongery of all kinds at a lower price than could the blacksmith. This put hundreds of country smiths out of business. But the preference and feeling for the home-made tool has lingered on, and is exemplified by the romantic, but often tragic, story of the travelling smiths of the 1890s who, like the former tramping artisans [22], roamed the villages seeking work at the diminishing number of smithies. They specialized in such highly skilled work as the doing-up of vice-jaws or making and repairing screw dies. Famous among them was a remarkable figure, known as 'Pincher Jack', who travelled all over England and Wales, stopping at the forges to make farrier's pinchers out of old rasps (figure 62 A). He is still remembered by countless older smiths as a tradesman of almost magical skill; and his legend illustrates the persistent, though not always justified, belief in the superiority of the hand-made tool over the factory product.

Improvisation played a large part in the village workshop, and influenced the design of future equipment. Examples are the famous stone-weighted beam-drill that operated without a screwing-down mechanism (figure 63); the post tire-bender in which the iron tire or strake was pulled into a circular shape without geared rollers (figure 62 C); and the home-made slip-wrench, an adjustable spanner made without a screw (figure 61 B) and much esteemed by tradesmen for its power to grip a worn nut.

The new factories recruited their craftsmen originally from the country workshops. Their skills survive in the tool-room and pattern-shop which control the factory's production, and among the maintenance engineers (the Jacks-of-all-trades still known as millwrights) who install and maintain the machines.

III. THE TOOL-MAKING TOWNS

Certain towns became centres of tool-making. Toledo and Damascus were famous for their swordsmiths in the Middle Ages (vol II, p 57). Solingen in Germany, Thiers in France, Sheffield in England, and the towns of Styria in Austria are among the places where for centuries a significant proportion of the world's hand-tools have been made. Styrian iron ores contain manganese, and the steel of the district was valued even in Roman times.

It is not definitely known why these places became centres of tool-making. Supplies of ore and wood fuel were to hand, and in some cases—for example, in the Styrian towns and at Sheffield—the streams provided water-power for tilt-hammers and grindstones (pp 32 and 34). But once the trade started, for whatever reasons, tradition would tend to confine it to these centres.

A high percentage of the inhabitants of these towns was occupied in tool-making. For instance, during the fifty years before 1600, more than half the bridegrooms married in Sheffield parish church were employed in the tool and cutlery trades. They were classed as follows [8]:

cutlers	122	scythe-smiths	3
scissor-smiths	42	file-smiths	3
sheathers	17	hammermen	1
shear-smiths	7		

When steel became more accessible after 1700 (p 34), and following the growing demand for hand-tools of every kind in the eighteenth and nineteenth centuries, Sheffield grew into a vast concourse of forges, operating not only in organized factories but in the back rooms of cottages, where much of the work was put out. Even today, once out of the commercial centre of Sheffield, the visitor can hear the ring of hammer on anvil in almost every side-street.

Many wooden tools—planes, coach-maker's routers (figure 62 B), malt-shovels, spoke-shaves, and saw-frames—were made outside the tool-making centres by small specialist firms such as those of the late Hannah Griffiths of Norwich [35] or Féron of Paris [51]. Tool-handles, flails, rakes, and scythe-shafts are still mainly produced by one-man concerns situated near the woodlands from which the timber is cut [6].

There is a popular notion that no steel is as good as it was before the 1914–18 war. Though it is true that war conditions contributed to the acceptance of inferior quality, the best makers continued to maintain a high standard, and still do so; but there seems no immediate prospect of an improvement in the cutting-life of even the best hand-tools. Indeed, the resistance to wear of such tools has not altered appreciably during the last hundred years.

IV. SPECIALIZATION OF TRADES

Any trade of considerable extent tends to produce specialists in its various branches. Within the primary trades of smith, mason, carpenter, and miller or baker there gradually appeared innumerable specialized crafts. Thus the smiths were divided into blacksmiths, tinsmiths, anchor-smiths, nail-smiths, shear-smiths, chain-smiths, and so forth. There was also a host of the less fundamental but highly skilled tradesmen, such as the spur- and bit-maker, gold-beater, pewterer, violin-maker, and glass-painter.

After the sixteenth century the number and variety of trades became very large. In 1574 the Swiss artist Jost Amman (1539–91) illustrated ninety different trades practised in his time [19]. Two hundred years later in the *Encyclopédie* Diderot described and illustrated over 250 [5]. In the next century Pigot and Company's commercial directory (London, 1826) records no fewer than 846 trades in London alone. It is true that some of the latter are of a very minor type—such as whalebone cutters, mourning-ring makers, hour-glass makers, whip- and stick-mounters—but each trade had its own techniques, and a considerable proportion of the different trades had each its own particular kit of tools, often supplied by a tool-maker who specialized in their supply.

The tool-kit considered necessary for different tradesmen has steadily increased since the sixteenth century. This is indicated in illustrations of a carpenter's workshop or tool-kit from the following sources:

Date	*Source*	*Number of tools in the picture*
1568	Jost Amman [19]	14
1703	Moxon [14]	30
1751	Diderot [5]	51
1892	Wynn Timmins's Catalogue [41]	90

V. SPECIALIZATION OF TOOLS

The differentiation of tools matched the rapidly growing multiplicity of trades.

One cause of the great variety in factory-made tools sprang from a desire to satisfy a demand that had been cultivated originally by village smiths, whose products tended to be characteristic of the region where they were made. This tendency is shown by the use of place-names and surnames to distinguish different tool-designs in the early pattern books of firms such as Isaac Nash [61]. Examples of these books are to be found in the Curtis Museum, Alton, Hampshire.

The 1905 catalogue of William Hunt and Son [44], among others, illustrates forty-two different shapes of bill-hook intended for laying hedges, cutting gorse, chopping firewood, and so on, many of which are named after towns or counties. In only a few instances is there a significant difference of function. Obviously this remarkable variety was designed to meet local demands. Farmers and householders bought originally from a local tool-smith, whose business could be captured by the factory only if the customer was supplied with the particular shape to which he had become accustomed.

Even in America, where the products of the factories are popularly supposed to have attained a high degree of standardization, the mail-order house of Belknap [42] lists over forty varieties of felling-axe, each made in six or more sizes.

The adze supplies an example of differentiation between trades. Thus the shipwright's adze differs from the wheelwright's (figure 64), and both differ slightly from the carpenter's. Yet these tradesmen could exchange adzes without suffering serious inconvenience. Similarly, a cooper demands a different type of wooden brace from that sold to the carpenter, while the chairmaker uses a third variety (figure 65). It may be suspected that such differences, though based on usage, were sometimes stimulated by the toolmakers, who sought to extend their business by offering tools intended to satisfy the needs of particular trades.

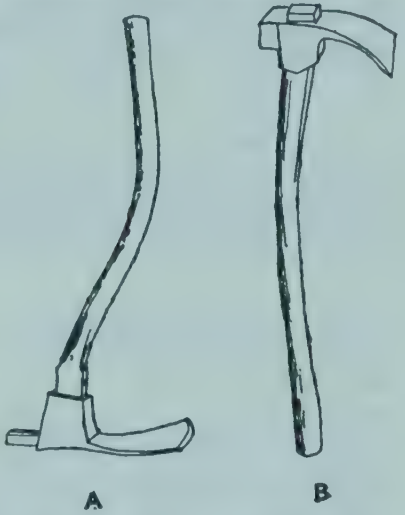

FIGURE 64—*Adzes.* (A) *Shipwright's adze with poll peg for driving in broken nails;* (B) *wheelwright's adze. The carpenter's adze resembles* B, *with the poll peg of* A. *Scale 1/12.*

Firms that made tools for an international market were obliged to carry stock as diverse as it was picturesque. The 1875 tool-list issued by Goldenberg & Cie, of Alsace [38], illustrates the following 'patterns' of adzes, axes, and trowels:

> Alsatian, American, Aragon, Asturian, Bavarian, Bayonne, Belgian, Berry, Bessarabian, Biscayan, Bordeaux, Brabant, Bresse, Castilian, Catalonian, Dutch, English, Flemish, Gotha, Greek, Hamburg, Havre, Hungarian, Italian, Kentucky, London, L'Orient, Lyon, Marseilles, Mexican, Moscow, Nantes, Narbonne, Neapolitan, Norman, Paris, Perpignan, Petersburg, Picardy, Pomeranian, Portuguese, Provençal, Saxon, Silesian, Spanish, Strasbourg, Swabian, Tartarian, Toulouse, Turkian, Yankee.

Not only do tradesmen living in different districts demand different varieties of tool but, fortunately or unfortunately for the tool-maker, there are strange

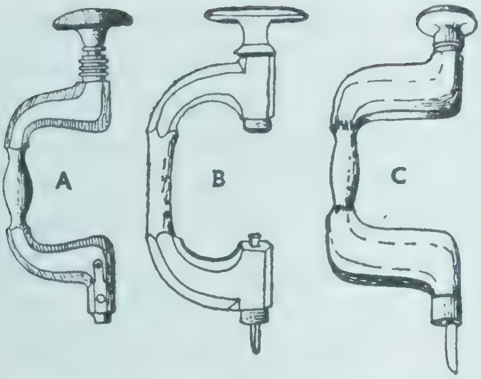

Figure 65—*Wooden braces.* (A) *Carpenter's and joiner's brace with latch chuck;* (B) *cooper's dowelling-brace with large head against which he pressed with his chest;* (C) *chairmaker's brace with small head fitting into wooden rest worn on the chest. Scale 1/10.*

inconsistencies. For instance, the cooper's axe used in the Liége district of Belgium [27] is precisely the same shape as the English coach-builder's axe; while the ordinary English cooper's axe is also used in many parts of Europe (figure 66). Yet no English wheelwright or coach-builder would dream of using a cooper's axe for trimming spokes or wedges, although it might serve him just as well as the coach-builder's axe.

A more functional differentiation applies to the chisel. Twenty-four distinct varieties were listed by a well-known London tool-merchant [45] about 1900, each with its own range of styles and sizes:

> Firmer, Butt, Buttonhole, Boxing, Coach, Millwright's, Paring, Registered, Barge Builder's, Mortice, Sash, Ship's slice, Mortice lock, Drawer lock, Flooring, Wagon Builder's, Wheelwright's, Ripping, Carving, Turning, Mason's, Bricklayer's, Engineer's, and Smith's.

In 1850 a firm of York plane-makers [34] listed twenty-nine distinct varieties of moulding-plane alone, and each variety was made in five or more sizes.

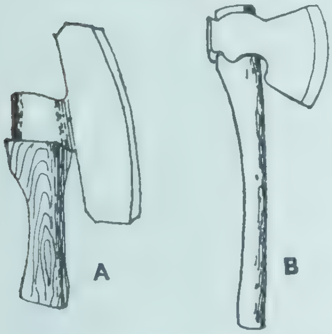

Figure 66—*Side-axes.* (A) *Cooper's type;* (B) *coach-builder's and wheelwright's type. Scale 1/12.*

The following are examples of exceptionally long lists of tools recommended for particular trades:

Philipson's 'Coachbuilding' (1897) [17] . . .	275	tools	and	appliances
Railway list for platelayer's tools (*c* 1950) . . .	159	,,	,,	,,
Forestry Commission tool-sheet (1951) . . .	173	,,	,,	,,
Saddler's tools (1950) [50].	112	,,	,,	,,

VI. THE ORIGIN OF SPECIALISTS' TOOLS

While the development of basic tools can be followed from the Stone Age, the derivation of the specialist's tool is more difficult to trace. If the etymology of their names can be taken as any guide to the date of origin of the tools, it appears certain that many of them were well known before the twelfth century. The following examples may be given as typical:[1]

The *bruzz* (figure 67 A) is the celebrated three-cornered chisel used by wheelwrights to chop out the corners of deep mortices; the name comes from the Old English word *brysan*, to crush.

The *auger*, the traditional boring-tool of shipwrights and wheelwrights, derives its name from the pre-twelfth-century English word *nafu-gar* which is formed from *nafu*, the nave of a wheel, and *gar*, a piercer. The *f* has been dropped, and the initial *n* was lost through confusion between 'a nauger' and 'an auger'.

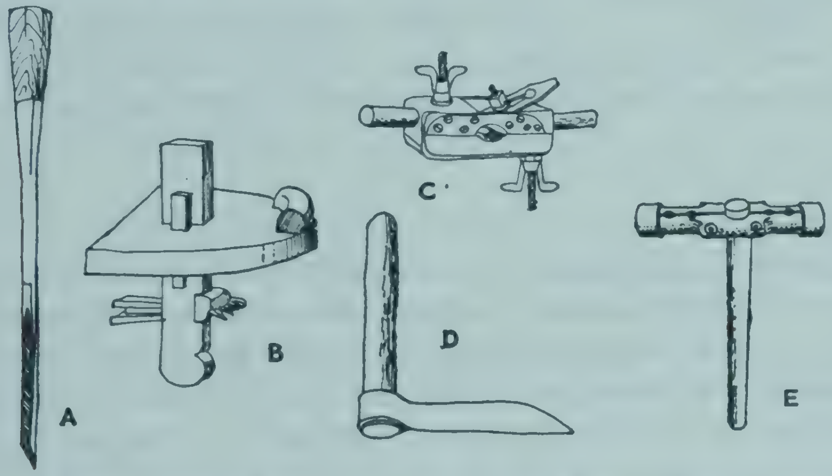

FIGURE 67—(A) *Bruzz or triangular chisel;* (B) *the croze;* (C) *nogg or moot;* (D) *froe or rending-axe, struck with a mallet on top of the blade;* (E) *shipwright's caulking-mallet. Scale 1/11.*

The *croze* (figure 67 B) is the cooper's tool for cutting a groove in the ends of the staves of a cask to receive the edges of the head; the name probably comes from the Old French *croz* meaning a hollow or groove.

The *nogg* or *moot* (figure 67 C) is used in many trades for shaping a rough stick into a round handle or dowel. (*Moot* applies particularly to the shaping of tree-nails for ships.) The origins of these words are obscure and may be much older than the other examples.

Some tool- or trade-names have almost disappeared from English workshop-language but are still in common use in the workshops of America. Examples are the Anglo-Saxon word *speech* meaning a wheel-hub with the spokes driven home but lacking the rim; and the word *froe* (figure 67 D), the name of a splitting-tool used for cleaving staves, spokes, or chair-legs. This tool is sometimes known in England as a *frower* or *frommard*, but is more commonly called a split-axe or rending-axe. The word *froe* probably comes from the Old English word *fromward*, meaning turned away.

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[1] Etymologies are taken from the Oxford English Dictionary.

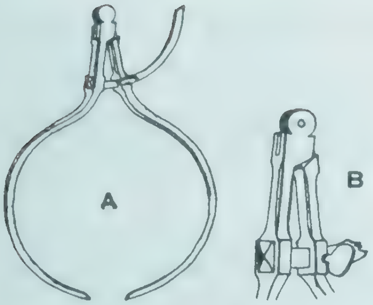

FIGURE 68—(A) *Wing calipers (scale 1/13)*; (B) *detail of stop-chamfering on calipers (scale 1/6).*

There are certain features in the design of hand-tools that have evidently survived for many years and are difficult to explain. For instance, the ball on one foot of the carpenter's pincers (figure 60 A) was possibly put there to provide metal for another claw on the other side. The slot cut through the head of a shipwright's caulking-mallet (figure 67 E) may be easier to explain. The split head deadens sound and gives enough spring to prevent stinging the hand. The old shipwrights liked to hear their mallets 'sing'; several men caulking a deck with ordinary mallets would deafen each other.

VII. DESIGN

Admiration for the artefacts of bygone civilizations should not lead us to overlook the merits of many common tools and utensils of trade in present-day use. Tool-making seldom produces an ugly object, for the design is a culmination of centuries of trial and error; and, as if by instinct, experienced tool-smiths tend to produce tools of graceful appearance. This tendency is apparent not only in conventional tools, such as the hedge-slasher and chisels and axes, but in some of the tools made for newly developed trades—for instance, in the garage mechanic's bi-hexagon ring-spanner (a direct descendant of the coach-builder's wheel-cap wrench) which, with its elegant curves, is an example of good industrial design.

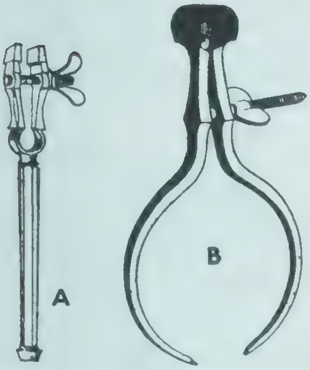

FIGURE 69—(A) *Watch-maker's pin-vice;* (B) *spring calipers with screw adjustment, hand forged. Scale 1/3.*

After about 1750 many of the most beautiful tools were forged in surroundings which pass belief for ugliness and squalor. For such was—and still continues to be—the scene in the overcrowded back-streets of many industrial towns. One such tool is the 'Lancashire' calipers (figure 69 B) shaped with the serpentine double curve recommended by Hogarth in his 'Analysis of Beauty' (1753); another, the all-metal Scotch brace; a third, the watch-maker's pin-vice (figure 69 A) They were produced by tradesmen who lived and worked for the most part in the darkest corners of the industrial towns.

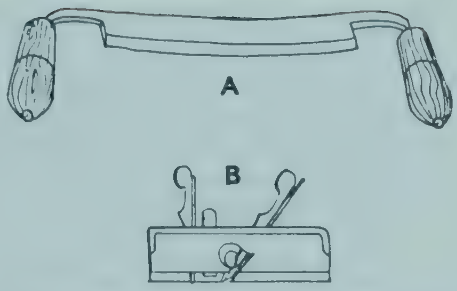

FIGURE 70—(A) *Draw-knife, used for shaping, cutting away, and chamfering;* (B) *trenching-plane for cutting grooves across the grain. Scale 1/12.*

An attractive feature of these metal tools is the custom of stop-chamfering (figure 68 B). This derives from the wain-wright, who applied a draw-knife (figure 70 A) to lighten the wagon's frame, stopping short of the joints where the full thickness is needed. It thus became a form of decoration. Much later this same finishing process can be seen on the connecting-rods of a locomotive, or on the forged frame of early bicycles.

In Italy and elsewhere in Europe during the sixteenth and seventeenth centuries (but not much in England) exquisite decorations and shapes of the kind developed by gun-smiths were applied to metal saw-frames and to surgeons' instruments—particularly the amputation-saw. This was done, perhaps, like the embellishment of sword-hilts, to give some ritualistic dignity to a deadly trade.

Wooden planes with beautiful though sometimes elaborate carvings were made on the continent of Europe during the eighteenth century. Many were imported into England, but, like the baroque in art, outlandish tool-styles never took hold in this country. The English tool-makers held to a tradition of severe but graceful lines (figure 70 B).

The Notes on pp 123 and 128 illustrate in more detail the use of specialized tools in two wood-working crafts which have survived with only very gradual changes of technique into the present century.

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A NOTE ON THE WHEELWRIGHT'S TRADE

J. GERAINT JENKINS AND R. A. SALAMAN

In many respects the craft of the wheelwright is similar to hardwood joinery, but whereas the joiner makes his joints to fit, relying a great deal on glue, the wheelwright relies on tightness of joints alone to hold the work together. He uses many of the same tools as the carpenter, and but few tools peculiar to his craft.

A wheel consists of a central nave, stock, or hub made of well seasoned elm, or less frequently oak, from which radiate an even number of cleft-oak spokes. The felloes, the curved members forming the rim of the wheel, are usually made of ash, but sometimes of beech or elm. An iron tire (or formerly a series of crescent-shaped pieces of iron called strakes) is shrunk on to the felloes to bind the wheel together.

I. THE NAVE

All the timber used in the manufacture of a wheel must be well seasoned, a process taking up to ten years. For the naves, straight smooth elms of suitable thickness are cut into lengths of 14 or 15 in; an auger-hole is bored through the centre to assist in drying, and the naves with the bark still on are stored until they are thoroughly dry. When the seasoning is complete, the dry naves are placed in a lathe and turned to the required shape and diameter. This shape is roughly cylindrical, a diameter of 12 in and a total length of $12\frac{1}{2}$ in being by far the most popular. In the past, when naves had to accommodate a thick wooden axle, the diameter was much greater.

After turning, the nave should have two gauge-marks on it. The first of these, 8 in from the hind end of the nave, acts as a guide for the front end of the spoke-mortises, while the other mark, $\frac{1}{2}$-in back from the 8-in line, allows for the staggering of the mortises. In the more recent type of hand-made wheel the spokes are generally staggered, so that one line of spokes has its front ends in line, while each alternate spoke has its front end a little behind its neighbour. If the spokes on a nave of small diameter were fixed in one line, then the mortises would weaken the nave. In the older, large type of nave this was relatively unimportant, for the dish or convex shape of the wheel was far more pronounced, and the spokes were generally fitted in a line.

Most cart- and wagon-wheels are 'dished' (figure 84), that is, the spokes make an angle of somewhat less than 90° with the hub so that they form a flat cone. As the axle bends down slightly, the lowest spoke (bearing the load) is perpendicular while the upper part of the wheel leans outward. Dishing has been both condemned and advocated: its chief merits would seem to be that it allows greater width in the body above the axle, and that mud is less likely to fall from the upper rim into the bearing. Further, a dished wheel is less likely to be forced out of shape by the sway or lateral movement of the body than a flat wheel.

II. MORTISING

After turning, the nave is placed on a low stool called a mortising-cradle (figure 71 (2)), and compasses are employed to mark out, by trial-and-error steppings, the centres of the required number of spoke-mortises on the gauge line. With a small try-square the centre line of each mortise is marked.

A spoke is now required in order to mark out all the mortises on the nave. By holding the 3 × 1-in foot of the spoke against the gauge line and directly over the centre line, the outline of the foot is marked in. The mortises are then bored with an auger or a 12- or 14-in sweep-brace with a 1-in bit. Three holes are bored, one at the front, one at the back, and one in the centre of each mortise-mark. The wheelwright depends entirely on his own judgement and skill for this operation, for the front hole has to be at a slight angle to allow for the dish of the wheel.

The next step is to chisel out the spoke-mortises, but before this is done a gauge known as a spoke-set gauge is prepared. This merely consists of a piece of hardwood 2 ft 9 in long, about $2\frac{1}{2}$ in wide, and 1 in deep. Some 4 in from one end a hole large enough to take a $\frac{7}{16}$-in coach-screw is bored, while at the other end a series of $\frac{3}{8}$-in holes, an inch apart, is bored. A piece of whalebone 9 in long is passed through the required hole and wedged there. The position of the whalebone depends on the size of wheel being made.

For example, to make a wheel 4 ft 10 inches in diameter, the position of the whalebone should be at half the diameter of the wheel (2 ft 5 in) minus the depth of the felloe (3½ in, for example), which would equal 2 ft 1½ in from the coach-screw pivot of the gauge.

The spoke-set gauge having been prepared, the next step is to plug the central hole that runs from one end of the nave to the other. With the compasses the exact centre of the nave-face is found, and at that point a hole large enough to take the coach-screw pivot is bored. The gauge is screwed up close to the face of the nave so that it is just possible to turn it without turning the nave. The main purpose of the spoke-set gauge is to measure the dish of the wheel; since the spokes in a dished wheel emerge from the nave at an angle, the spoke-mortises also have to be cut at an angle. The whalebone of the gauge is set to the point where the spoke will enter the felloe; that is, 2 ft 1½ in from the central pivot in a 58-in wheel. Next, the distance between the gauge and the turner's face-mark at the base of the front spokes on the nave is measured. In a nave 12½ in long it

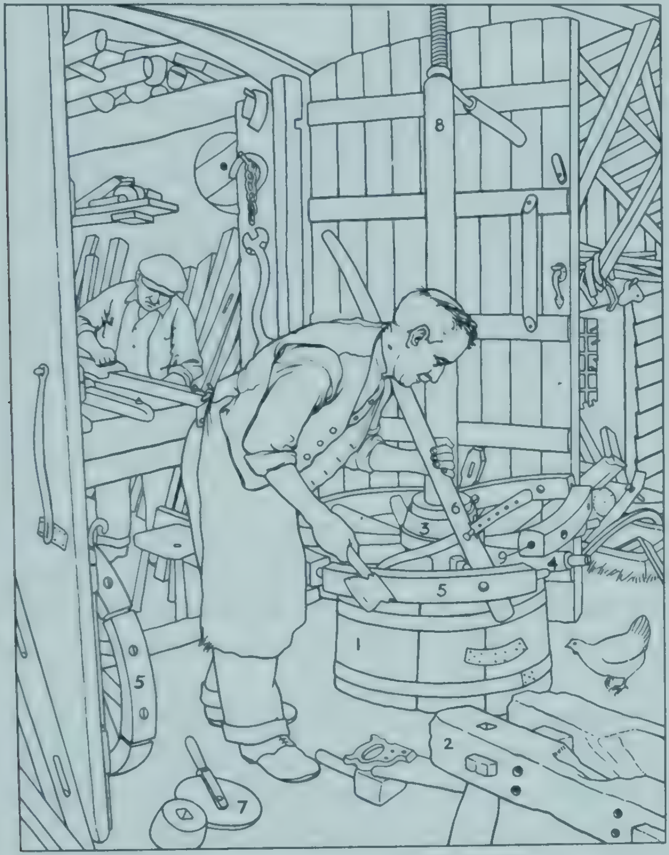

FIGURE 71—*Wheelwright's workshop. He is fitting the felloes on the spokes, using a spoke-dog to strain two spokes together so that their tongues will enter the holes* (*p 127*). (1) *Wheel stool;* (2) *mortising-cradle, for holding the wheel nave* (*see* 3) *while the mortise holes are cut to take the feet of the spokes;* (3) *nave;* (4) *spoke;* (5) *felloes, forming the rim of the wheel;* (6) *spoke-dog;* (7) *traveller, for measuring the circumference of the wheel and for marking off the same length on an iron bar for the tire;* (8) *cramp, for holding the wheel steady when fitting the felloes* (*see further plate* 6).

will be 4½ in, as the face-mark is 8 in from the back end of the nave. If one requires a ½-in dish on the wheel, then the whalebone should project 4 in beyond the stick. In cutting the mortise, the slant of the boring must be such that a narrow straight-edge held against the front of the mortise just touches the whalebone. The reason for using a springy whalebone gauge, rather than a rigid stick, becomes apparent when the spokes are being driven into the nave.

A number of tools are required to prepare the mortises. The first of these is a mortising-bruzz; this is a long socket-handled chisel with a V-shaped blade (figure 67 A). The bruzz is used for cleaning the corners of the mortise; a 2-in firmer chisel is required to cut the core. To pare away the front and back ends of the mortises ¾-in and 1-in heading-chisels are required. Lastly the workman requires a heavy mallet, and a pair of inside calipers with which to check the size of the mortise as the work proceeds.

When all the mortises are complete, the nave is taken to the blacksmith in order to have the iron breast- and hind-bonds shrunk on. To prevent these bonds slipping, three nails of special shape are hammered into the nave, resting against the front end of the breast-bond and the back end of the hind-bond.

III. SPOKES

The naves are now ready to receive the spokes. These are of straight-grained oak, cleft from a clean, straight trunk while still green, and seasoned for four or more years. They are roughly shaped with the side-axe (figure 66 B) and finished with a spoke-shave to the required size. The foot of the spoke is then shaped to form a tenon 3 in long and 1 in wide (vol II, figure 505).

The nave is placed over the wheel-pit for the spokes to be driven in. This wheel-pit is rectangular in shape and measures some 6 ft in length and 10 inches in width. To provide a solid base for the nave while the spokes are being hammered in, the sides of the pit are bricked or lined with timber. While one man holds the nave steady and keeps the spoke in an upright position, the other swings a 14-lb hammer to drive the spokes into place. After every two or three blows, the spoke-set gauge is pushed into position, to ensure that the spoke is entering at the correct angle. Since the tenons are tapered, each blow of the sledge makes the spokes tighter in the nave and therefore progressively more difficult to correct. If the spoke is driven in at the wrong angle despite the efforts of the wheelwright to correct it, then it must be left until the adjacent spokes have been fitted. He then places a curved piece of ash, 2½ ft in length, known as a 'crooked stick', behind the spoke that is to be pushed forward and in front of the adjacent spokes. While the misdirected spoke is thus forced against the gauge it is again hammered; hence the use of a flexible 'feeler'. When all the spokes are in place, the wheel is measured with the spoke-set gauge to ensure that it has the right dish.

The next step is to set out the tongues of the spokes. In the days of broad straked wheels—mainly before 1850—the tongues were square and square mortise-holes were cut in the felloes to take them. Round tongues, far easier to make and fit, were used later. A scribe, consisting of a piece of ash 2 ft long and ¾-in square with a bradawl inserted, marks out the shoulder on the face of the spoke. The scribe is placed along each spoke, its foot resting firmly at the point where the spoke enters the nave. The shoulder is then scribed. In a wheel with a diameter of 4 ft 10 in, the shoulder will be 1 ft 7½ in up the spoke from the nave. When this is done a felloe-pattern is placed over the scribed spokes to ensure correct fitting. The front shoulder, then the back shoulder, are cut with a tenon-saw and chisel, and the tongues are trimmed to a slightly oval shape.

IV. FELLOES

In the past, felloes were sawn with a thin-bladed frame-saw (figure 61 E), each felloe conforming to one of the many patterns kept by the wheelwright in his shop. Today they are sawn with a band-saw. After sawing they are trimmed with axe and adze where necessary, and then smoothed with planes. To fix the felloes, the wheel is placed face downwards on the wheel-stool. The correct angle at the ends of the felloes is obtained with a small bevel, and each tongue is marked on it. A gauge is set to mark out the centre of the spoke-holes on the felloes, and these are bored with a 1½-in auger. When all the boring is completed, the next step is to make the dowels joining the felloes. These are short rods of oak, 4½ in long and 1 inch in diameter. When in place each dowel projects 2 in beyond the end of the felloe and each one is slightly rounded at the top, to ease the joining of the felloes.

With the wheel so far prepared, the felloes now have to be fitted to the spokes. The wheel is placed face downwards on the stool, and a felloe tapped some ¾-in down the tongue of a spoke. The second spoke will not at first enter the second hole in the felloe, owing to the radial divergence of the spokes, which causes the tongues to be wider apart at their ends than at the shoulders. To bring two spokes together, so that a felloe can be slipped on easily, a 'spoke-dog' is employed to bend them (figure 71 (6)). As the wheelwright presses the handle of the spoke-dog forward, the spokes are bent and a felloe can easily be tapped on. When all the felloes have been fitted, wedges are driven into the split ends of the spoke-tongues, which are recessed in the felloe so that they will not touch the tire.

The completed wheel is then placed on the wheel-stool or stand, checked with various gauges, and finished with plane and spoke-shave.

V. TIRING

From the wheelwright's shop, the wheel is taken to the blacksmith for tiring. A bar of iron 16 ft long, 2½ in wide, and ¾-in thick is laid flat on the ground. A chalk-mark is made on the rim of the untired wheel, and another mark on the measuring-wheel or traveller (figure 71 (7)). With the chalk-marks as starting-points, the traveller is pushed round the rim of the wheel and the number of turns noted; then it is run along the bar of iron. This measures the wheel's circumference, but allowance has now to be made for the overlap at the weld and the expansion of the tire when heated. The bar is passed between a series of rollers to be bent to the required shape and the two loose ends are then welded together. In the older country workshops the iron was bent by hand on a post bender (figure 62 C).

The untired wheel is screwed down firmly on the circular iron tiring-platform, which is a permanent fixture in the blacksmith's yard. The tire-hoop is heated on a fire of straw and shavings; when it is sufficiently expanded it is carried with long-handled tongs to the tiring platform and with tire-dogs forced upon the wheel. Water is then poured on the rim, and as the tire shrinks the wheel is tightened under the enormous pressure of contraction.

VI. BOXING

Finally, the cast iron bearing or box has to be fixed in the centre of the nave. A large, tapering hole is cut through the centre of the nave with heavy boxing-chisels and gouges, or more recently with a tool called a boxing-engine, which is a revolving cutter working on a threaded bar. The cast iron bearing is loosely fitted into the nave, and adjusted by trial and error. The axle-arm is temporarily fixed to a bench, and the wheel hung on it so as to turn just clear of the ground. A small block of wood is then placed on the floor, just touching the edge of the tire. Slowly the wheel is turned round, and as it swings clear of the block, small oaken wedges are hammered into the end-grain of the nave around the box. The process is continued until the box is centred and firmly wedged in the nave. All that remains is to chisel off the ends of the wedges, and after smoothing and painting the wheel is ready.

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A NOTE ON COOPERING

J. GERAINT JENKINS AND R. A. SALAMAN

COOPERING is the making and repairing of wooden vessels formed from staves and hoops. The cooper has few written measurements and patterns; tradition is his main guide even when making a vessel of specified capacity and girth. He must know the numbers and dimensions of the staves for a vessel of a particular size, and must shape them to fit accurately. Coopering is one of the few surviving crafts in which machine-techniques have not entirely replaced age-old methods of handicraft.

The craft was developed in ancient Egypt (vol I, figure 500), was well known in Roman times, and survived through the Middle Ages. The growth of trade, especially by sea, increased the demand for casks of standard capacity. On ships almost everything was stored in casks, and the cooper continued to be an important member of the crew until the mid-nineteenth century. On land, coopering was essentially a guild-craft, but by the end of the nineteenth century master-coopers had become few and most of the workshops were in breweries.

The least specialized branch of the trade is that of the dry-cooper, who makes casks for solid materials such as flour, tobacco, sugar, or crockery. His work is far less exacting than that of the wet-cooper, for the staves need not be so tight, and the barrels can be bound with ash or hazel hoops and are far less bulged. Douglas fir is the wood most commonly used for the staves, but elm, spruce, poplar, and beech also serve. In this branch of coopering, machinery early replaced hand-work. The staves are arranged inside a hoop until a complete circle is formed. They are then steamed until pliable, and a windlass is employed to draw together their free ends into a barrel-shape. Thus bent, they are heated to set them. For special purposes the technique of wet-coopering is adopted even for containers of dry goods.

The second branch of the craft, white-coopering, disappeared almost completely in the late nineteenth century. The white-cooper made pails, butter-churns, wash-tubs, and so forth for dairy and household use. He worked almost exclusively in villages and small towns. Some idea of his range of products is given by a rhyming signboard of the early nineteenth century from Hailsham, Sussex:

As other people have a sign,
I say—just stop and look at mine!
Here, Wratten, cooper, lives and makes
Ox bows, trug-baskets, and hay-rakes.
Sells shovels, both for flour and corn,
And shauls, and makes a good box-churn,
Ladles, dishes, spoons, and skimmers,
Trenchers, too, for use at dinners.
I make and mend both tub and cask,
And hoop 'em strong, to make them last.
Here's butter prints, and butter scales,
And butter boards, and milking pails.
N'on this my friends may safely rest—
In serving them I'll do my best;
Then all that buy, I'll use them well,
Because I make my goods to sell.

Oak was the main material of the white-cooper, but he used also ash and sycamore. The ways of making a tub or bucket were much like those of the wet-cooper, except that the shave was used to cut across instead of along the grain of the wood when smoothing the inside.

The third, the commonest, and the most highly specialized branch of the craft is wet-coopering, that is, making water-tight casks for liquids. It is exacting work, for not only must the staves fit accurately but the cask must be able to withstand the strain of fermenting liquids and rough handling during transport. Moreover the cask must be of an exact capacity. The only timber used is oak: American is preferred for spirits, Mediterranean for wine, and northern European for beer. Different qualities of wood are required for different classes of work; thus porosity is essential for some wines to allow the passage of air through the wood to assist fermentation. For spirits, cleft staves cut along the radius of the tree-trunks are used; this is because, conforming to the natural concentric rings of the tree, the wall of the barrel thus becomes so close-knit that neither water nor alcohol can pass through.

The craftsman's task begins where the woodman's ends (figure 72). Trees of about two hundred years old and of trunk-diameter between 18 and 24 in are cut into the lengths of staves. The logs are cleft into quarters with hammer and wedges, and further broken down to the required shape with a long-handled split-axe (figure 67 D). They are then shaved with a draw-knife (figure 70 A) and cut to the exact length of the required staves with a cross-cut saw. Trees of over 24 inches in diameter are used for headings. The rough staves are dried by piling in the open for a period dependent on climatic conditions, and are then placed in a kiln and further dried to a uniform moisture-content. The final embodiment of these staves into a tight cask involves the following stages.

1. *Preparing the staves.* The roughly shaped stave is clamped in a shaving-horse or firmly fixed in a hook on the cooper's block, which is a tree-trunk about 2 ft high. The smaller staves of casks holding less than 9 gallons are clamped on the sloping table on the front of the horse. The cooper sits astride the horse, regulating the pressure on the clamped stave with his feet. For the larger staves, the wood is merely held in a toothed hook on the top of the block. The outside of the stave is shaped with a draw-knife. The stave is then reversed, and a round-bladed draw-knife is used to shape its inner side.

In a cask the staves are narrower at the ends than in the middle, and the taper is first obtained with an axe sharpened on one side only, with the handle bent towards the sharpened side to prevent the cooper from knocking his knuckles against the stave as he shapes it (figure 66 A). This done he pares down the sides of the stave with a draw-knife, the stave being still held in the shaving-horse.

The sides are then bevelled, according to the radius of the cask, on the long jointer-plane. It stands upside down, one end on the ground, the other on a frame socketed loosely into a mortise at the front. This elevates the plane towards the cooper and enables him to smooth-edge a stave by sliding it downwards over the blade of the upturned sole. This plane may be as much as 6 ft long, while the front end stands some 2 ft high.

2. *Raising the cask.* The staves are arranged inside an iron raising-hoop until a complete circle is formed. An ash truss-hoop, which will be removed later, is driven down to hold the staves in place. The cask at this stage has the appearance of a truncated cone, the staves being held in place at the top by the iron raising-hoop, and splaying outwards to be held at a lower level by the ash truss-hoop. The cask is now said to be 'raised'.

3. *Trussing and bending.* To make the timber pliable for further work it has to be steamed. In large workshops the raised cask is placed in the steaming-chest for twenty minutes. More usually the staves are moistened and the cask is placed over a brazier containing a fire of shavings. This softens the fibres so that the staves can be bent. For wine-casks of the more pliable Mediterranean oak, a rope-and-tackle is passed around the open end of the staves, drawing them together into barrel-form, in which they are

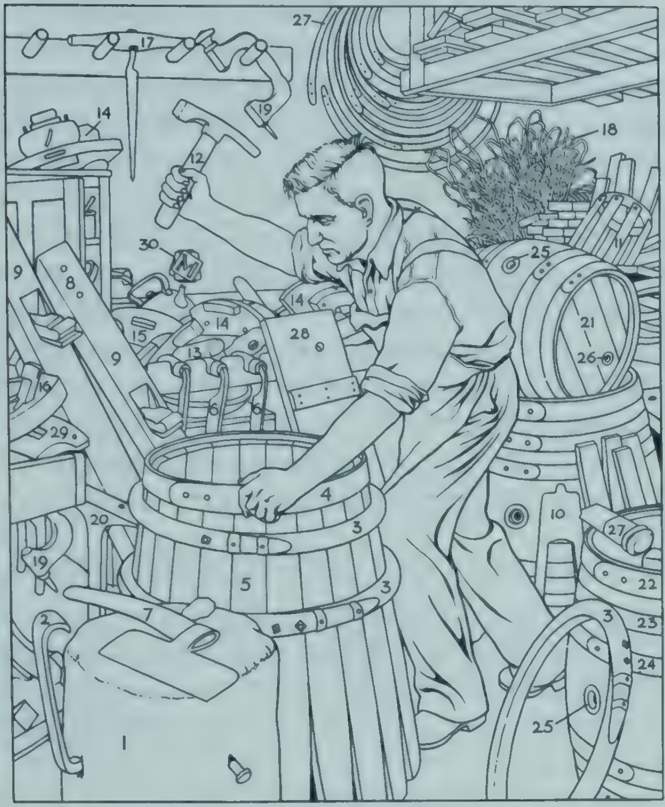

FIGURE 72—*Coopering. The cooper is raising a cask, driving on the truss-hoops (p 130).* (1) *Block;* (2) *block-hook, for holding staves while they are shaped with a draw-knife;* (3) *wooden truss-hoops for holding staves in place during assembly;* (4) *iron raising-hoop, for holding a circle of staves when raising the cask;* (5) *stave;* (6) *drawing-knives and heading-knives;* (7) *side-axe, used for trimming staves, heads, etc.;* (8) *holes in jointer to take stool (see* 10); (9) *jointers, for planing the edges of the staves;* (10) *stool, on which the jointer rests when in use. The spigot at the top fits into the hole (see* 8); (11) *cresset or brazier, for holding the fire heating the inside of the cask when bending and setting the staves;* (12) *trussing-adze, used for driving the truss-hoops when raising the cask;* (13) *sharp or rounding adze, used for cutting the chiv, in place of the chiv-plane (see* 14); (14) *the chiv-plane in various sizes, for cutting the shallow channel below the top of the staves, in which the groove to take the head is later cut with a croze;* (15) *downright, a shave for smoothing the outside of the cask;* (16) *stoup, a compass type of plane for smoothing the inside of the cask;* (17) *taper auger, for cutting a tapered hole to receive the bung;* (18) *flags: dried rushes used for caulking joints between head and croze, and other joints;* (19) *brace, with shell bit, for boring the holes to take the dowels which join the separate boards of the head (see* 21); (20) *bick-iron, on which the hoops are riveted;* (21) *the head of the cask;* (22) *cap or chime hoop;* (23) *quarter-hoop;* (24) *bilge-hoop;* (25) *bung-hole;* (26) *tap-hole;* (27) *hoop-driver;* (28) *board used for holding head during planing;* (29) *heading-swift, for planing the heads;* (30) *letter stencils, for marking the casks (see further plate 7).*

held by iron or sometimes wooden hoops. The staves of beer-casks, on the other hand, are usually too thick and stiff to be thus drawn together. The cooper therefore bends their splaying stave-ends by driving on progressively smaller ash truss-hoops. These are beaten down with a heavy trussing-adze. The cask is then again placed over the brazier for some fifteen minutes to remove moisture absorbed during the steaming. This heating is also said to shrink the fibres of the wood on the inside of the bulge, which helps to set the staves in barrel-form so that when the truss-hoops are removed they will not spring out of position.

4. *Topping.* The ends of the cask staves are now trimmed with an adze to form a bevel (the 'chime'). This special cooper's adze has a short handle, about 9 in long, so that it can be swung within the radius of the cask. The ends of the staves are finished off with a topping-plane having a semicircular stock and a flat sole. A fairly broad but shallow channel (the 'howel') some 2 in below the top of the staves is then made with a special plane called a chiv. For repair-work the channel is cut with a hollow-bladed draw-knife or jigger. A deeper but narrower channel in the middle of the chiv-cut, into which the head fits, is cut with a croze (figure 67 B). Like the chiv, the croze is provided with a large semicircular fence which bears on the rim of the cask. It is more like a giant carpenter's gauge than a plane, the peg which carries the cutter passing through the fence and being adjustable by a wedge. The cutter consists of three saw-teeth set coarsely to cut a wide groove, or of a single hawksbill tooth of the router kind. The fence is placed horizontally on the rim of the cask and the blade set at the required distance below it. As the instrument is pushed around the inside of the tops of the staves, the circular groove to receive the head is cut.

5. *Cleaning down.* Various shaves are taken to smooth both the interior and exterior of the cask. Since the cask is set, all but the end hoops can be knocked off. A small 'downright' shave with its cutting-edge slightly concave is now pushed down the outside and gives the first rough shaping. This is followed by a scraper-shave. For the inside, a tool similar to the downright shave, but with a convex blade, is pulled along the joints towards the operator.

6. *Bunging.* The bung-hole is now bored with a taper-auger and then smoothed with a conical burning-iron. The rough edge inside is trimmed with a hook-like knife oddly called a 'thief'. In beer-barrels a bung of cork is used temporarily, but later a thin wooden cylinder or shive is driven into the bung-hole. When the whole cask has been assembled, another tapered hole is bored through the head, which is stopped by a cork until the tap is fitted to it. Since beer would not flow without an air-inlet to the barrel, after fitting the tap a small hole is pierced through the shive. This hole is stoppered by a tapered peg known as a spile.

7. *Heading.* The heads are of three or more pieces of oak held together by dowel-pegs, and caulked between joints with dry rushes (see 8). The dowel holes are drilled with a brace and hollow bit (figure 65 B). To obtain the approximate radius of the head the cooper proceeds by trial and error, stepping his compasses around the groove at the top of the cask until the circuit is completed in six equal steps or chords. The distance between the compass-points is now equal to the radius of the cask head. The head is rested on the block, being supported by the cooper's left hand and body. It is then shaped with the side-axe, and bevelled along the sides with a draw-knife. The head is planed across the grain with a heavy shave ('heading-swift') fitted with a 2½-in cutting-iron. While the cask-head is being inserted, it is held up by means of a coarse screw twisted into it and removed afterwards. The temporary chime-hoop is taken off, and the head is eased into position. An iron bar, bent at one end, is introduced through the bung-hole to knock up the head if it falls below its groove.

8. *Caulking or flagging.* The dried rushes (or 'flags') for caulking the joints of the head, and the space between the head and its groove, are pushed in with a chisel-like tool. In repair-work, and often in manufacture, rushes are inserted between the staves, but only from their ends down to a point above the bilge. A fork-like tool ('flagging iron') is used to spring each stave in turn, opening the joint sufficiently to receive the rushes. On the continent of Europe other types of tool are used for this purpose. One such is illustrated in a Jost Amman woodcut of 1574 (p 122, reference [19]).

9. *Fitting the hoops.* The iron hoops are cut, beaten into shape, and riveted on the T-anvil. They are driven into place with a hammer and a driver; the latter is a steel wedge-shaped tool with an oaken handle, grooved at the narrow end to prevent it from slipping off the hoop. Finally, graduated sticks called diagonals are used to make sure that the cask will hold the correct volume.

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6

FARM-TOOLS, VEHICLES, AND HARNESS 1500–1900

OLGA BEAUMONT (I, III) AND J. GERAINT JENKINS (II)

I. FARM-TOOLS

THE majority of the small farm-tools used between 1500 and 1900 were traditional, varying from medieval types only in details of design and in materials of construction. The slow progress of invention before the industrial era is clearly demonstrated by the works of agricultural theorists writing in the sixteenth and seventeenth centuries, such as Thomas Tusser, Gervase Markham, Walter Blith, and John Mortimer. In his 'Five hundreth good pointes of husbandry' (1573) Tusser gave a list of tools necessary for the farmer, including a flail, straw-fork, rake, pitchfork, dung-fork, shovel, and spade. In fact, farms normally possessed, in addition to a plough, a wain, and a tumbril, a small collection of spades, weeding-tongs, forks, sickles, and flails. Subsistence agriculture could scarcely have been practised with less equipment than this.

Digging, harrowing, and drainage. In the sequence of preparing ground for seed hand-tools often had their place between the original ploughing and the final smoothing with a harrow (figure 73). The soil was broken up with spades, mattocks, and clodding-beetles of various shapes. A wooden spade with a two-sided blade and a metal tip was used at the beginning of the period, but blades made entirely of metal came into use later. Tools for breaking clods varied in design from mallet-shaped beetles to flat stampers and hacks with straight or curved blades. As methods improved and harrows and cultivators came into more general use these implements were superseded.

A number of writers after 1660 described the use of the breast-plough (figure 74) for cultivating small areas and paring weeds off the surface of the ground. John Mortimer in 'The whole art of husbandry' (1707) referred to its use for paring and before burning in the counties of south-west England. The most common type had a stout handle 5–8 ft long forking at the top and mortised to a cross-piece. The blade was about a foot long and 18 in wide with a flange or coulter by which the slice was cut. By pushing against the cross-piece the operator forced the blade along under the surface of the ground and cut a thin broad slice 2 or 3 in thick. In 1802 Sir John Sinclair, president of the Board of Agriculture, advocated the breast-plough for reclaiming waste land in Scotland, but it was no longer in general use after the middle of the nineteenth century.

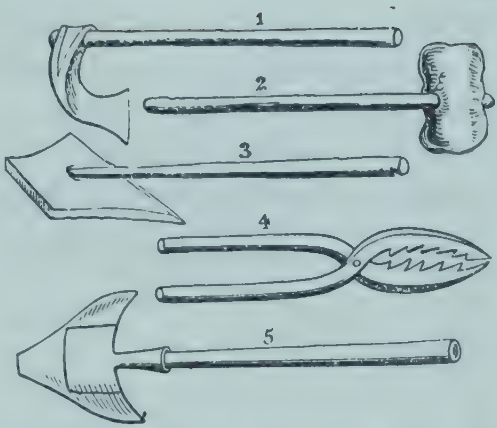

FIGURE 73—*A selection of seventeenth-century farm tools, from Gervase Markham's 'Farewell to Husbandry' (1620).* (1) *Hack for breaking clods after ploughing;* (2, 3) *clodding-beetles;* (4) *weeding-tongs;* (5) *paring-shovel for clearing ground and destroying weeds.*

Hand-tools were the only implements used for drainage until the end of the eighteenth century, when drainage-ploughs were invented. The topic was frequently discussed in books on farming between 1600 and 1800, and Walter Blith gave a careful description of drainage tools in his 'English Improver Improved' in 1652 (figure 75). Spades of varying widths were necessary for the different stages of trench-construction. One form of spade pushed before the worker had two horn-shaped projections at the side, which cut the turf. Towards the end of the period brush- and stone-filled drains were gradually superseded by arch-shaped drainage-tiles, and ultimately by round tiles placed edge to edge to form pipes (vol IV, ch 1).

Sowing. The earliest and simplest way of sowing seed was to broadcast it, a method still practised by many farmers in the late nineteenth century. The sower carried the seed in a sheet, basket, or wooden seed-lip slung over his shoulder; walking up and down the ridges of the field, he scattered handfuls of grain by rhythmical sweeps of his arms across his body. Great skill was necessary to ensure even distribution of seed.

A second method of sowing, known as dibbling, was common before mechanical drills became popular, particularly for large seeds such as beans. Holes were made in the ground at regular intervals by a man walking backwards and carrying in each hand a pointed iron rod or dibbler (figure 76, right). This tool was about 3 ft long with a handle like that of a spade and a tapering knob at the bottom. Women and children followed dropping seeds into the holes. A wooden setting-board measuring 3 ft in length and a foot wide with spaced holes for seeds was described by Sir Hugh Plat in his 'Newe and admirable arte of setting of corne' (1601). Men standing or

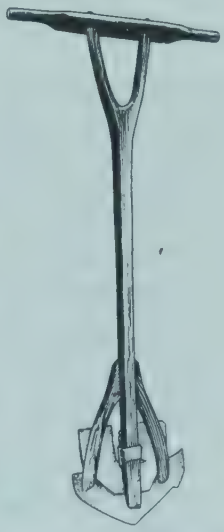

FIGURE 74—*Breast-plough, 5 ft 3 in high; the cross-piece is 2 ft 4 in wide.*

kneeling on the board could push their dibblers and seeds through the holes. This method was laborious in practice, and the device was never widely used. After 1800 drills began to replace all other methods of sowing.

Weeding and hedging. Tongs with teeth, originally made of wood and later of metal, were necessary for the important task of weeding. An implement with two large prongs and a third prong curled up behind to give leverage was also used, particularly for docks, a common weed in pastures. Arable weeds could be controlled by the combination of a small knife on a long handle and a forked stick to hold the weed still while cutting. One tool was held in each hand. Thistles were cut with scythes or bruised with thistle-spuds before the formation of seeds.

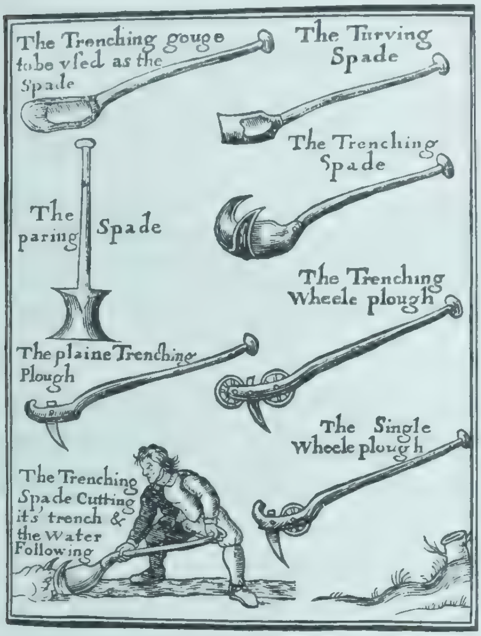
The Trenching gouge to be vſed as the Spade
The Turving Spade
The Trenching Spade
The paring Spade
The Trenching Wheele plough
The plaine Trenching Plough
The Single Wheele plough
The Trenching Spade Cutting its' trench & the Water Following

FIGURE 75—*Drainage-tools, from Walter Blith's 'English Improver Improved', 1652.*

Hedges became characteristic of the English landscape as the medieval open-field system gradually disappeared. The enclosure of open fields proceeded throughout the period, and plots were separated from surrounding land by hedges, stone walls, or fences. Large hedging-hooks and smaller-sized bill-hooks were used for the work of laying, cutting, and trimming hedges (figure 76, lower left). Each district had its own pattern. The traditional regional shapes first forged by local blacksmiths are still followed by modern manufacturers (p 116).

Harvesting. Before the invention of mechanical reapers crops were harvested by hand with the aid of sickles, hooks, and scythes. The sickle (figure 76, left) was the earliest implement for reaping corn (vol I, pp 513–14, 541–2; II, p 94), and the form of its continuously curved blade ending in a sharp point several inches beyond the line of the handle remained unchanged from the eleventh century. Some sickles had plain blades, others had serrations along the blade except for the last inch or two at the tip. This tool was intended to cut the corn handful by handful, the stalks being held in one hand by a man stooping or kneeling and cut by a swinging motion of the sickle in the other hand.

Sickles were often replaced by hooks in the mid-nineteenth century. These tools had larger, less curved blades and slashed rather than cut. The man who reaped with a hook carried in his other hand a short wooden crook which he used to draw the crop forward towards himself.

The scythe (vol II, p 95) was a common tool for grass-cutting throughout the period, and its use for reaping oats, barley, and wheat gradually increased. It consisted of a broad metal blade mounted on a wooden pole to which two handles were attached. Medieval illustrations show scythes with straight poles (vol II, figure 62), but curved poles of willow had come into use by the end of the seventeenth century. A light wooden frame or 'cradle' curved parallel to the blade of the scythe collected the stalks during the process of mowing, so that they fell in compact even rows.

After reaping, the swaths of grass were thrown about with wooden forks or hay-tedders and spread evenly over the ground to dry. When dry, the hay was collected into wind-rows with drag-rakes. It was later pitched into a cart and from cart to stack by forks. Grain was tied in sheaves by women and children (figure 77). It was allowed to stand in stooks before being loaded on to a cart with pitchforks. The continuity in the design of the pitchfork and drag-rake over a long period of years can be seen by comparing eighteenth- and nineteenth-century illustrations with modern examples.

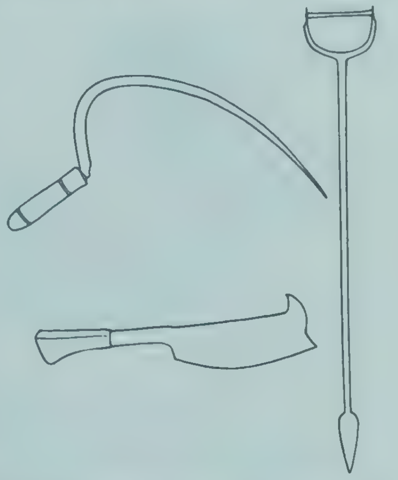

FIGURE 76—(Right), *Dibbler used for sowing seeds;* (left, above), *sickle from Gloucestershire; the strongly curved blade is more than 22 in long;* (left, below), *bill-hook of Northamptonshire design. Scale 1/14.*

Threshing. The flail was the implement in general use in all north European countries before the mechanization of threshing. Its two principal parts were the hand-staff, a straight slender stick of ash or beech 4 or 5 ft long, and the swingle or beater, a shorter, stouter stick of holly, blackthorn, or some other hard wood, about 3 ft long. The two parts were fastened together loosely by thongs, which allowed angular movement in every direction. The proportions between the two parts of the flail and the precise method of joining varied in different areas.

Threshing by flail normally took place in the winter months and was a very skilled operation. The hand-staff was grasped with both hands, at a short distance from one another, and raised so that the swingle flew round the thresher's head and came down with a heavy blow on the ears of grain (vol II, figure, p 102). The work was done in barns, which were often constructed especially for threshing. They had a central strip or threshing-floor where the work was done. The floor was made of hard, beaten earth, oak-planks, or stone. Small compartments were built on either side of this strip, and the barn had a door high enough to drive a loaded wagon through. Sheaves were placed in one compartment and threshed, and the straw was stacked in a corresponding division on the other side of the barn.

To remove coarse material after threshing the grain was sieved through a wide round riddle with meshes of ash or split willow. Corn and chaff were separated by winnowing, either on the top of a hill or in a barn. The mixture was tossed into the air using wooden shovels or shallow wicker baskets. The wind carried away the chaff and let the grain fall back to the ground or threshing-floor. To assist in winnowing, barns were often built so that the wind blew directly through them. An artificial draught could be created by the use of a crude winnowing-machine, made of wooden arms with sacking attached and mounted on rough bearings. As the handle was turned round by one man a second threw the grain in front of the machine from a shovel or hollow tray made from a single piece of birch or sycamore.

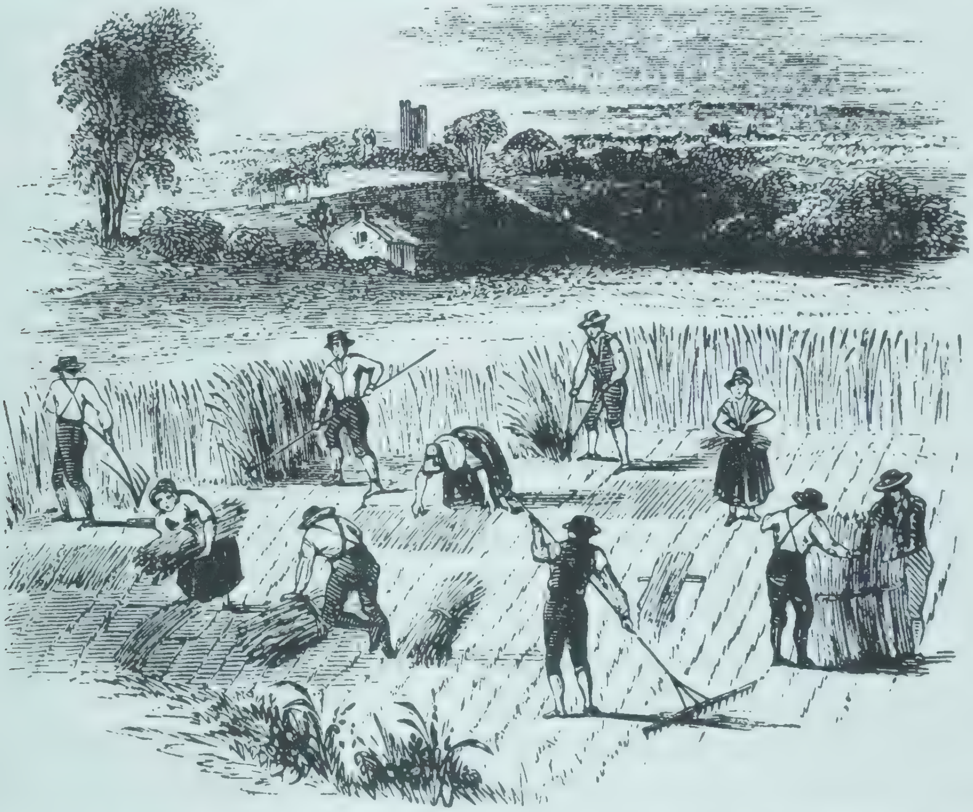

FIGURE 77—*A nineteenth-century harvest scene showing the use of scythes and a drag-rake and the binding of sheaves. c 1840.*

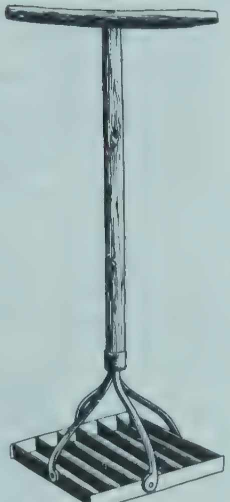

FIGURE 78—*Barley-awner of the early nineteenth century used in Hampshire.*

Awners were used to cut the awns or beard off barley. Several varieties existed, the most common consisting of a square iron frame containing parallel blades and a short handle set vertically in the frame (figure 78). The barley was heaped, and struck with this frame. When a rotary awner with blades set round a drum was used the implement was rolled over the grain in lawn-mower fashion.

Agricultural development depended upon dissemination of new ideas, availability of suitable materials for the manufacture of implements, and improvement of transport. The gradual adoption on some farms of new and more complicated implements for all the operations of the farming year did not bring about the complete abandonment of the old tools locally made. The new and the old often co-existed. In Britain machines have now replaced most of the hand-tools, but there are still some survivals on modern farms, such as tools for hedging; they are closely related to the medieval types. Farther afield in Europe, in places where mechanization has not completely altered the nature of farming, the scene at such times as harvest is little different from that which might have been witnessed in fourteenth-century England.

II. AGRICULTURAL VEHICLES

Sledges and pack-animals. Despite the general improvement in agricultural transport in the sixteenth century, isolated and hilly districts still clung to the more primitive methods. In those districts human porterage remained very common for short distances, while pack-horses, mules, and asses were used to carry loads for longer distances.

The simplest, and probably the oldest, method of carrying goods was on the backs of men. Nevertheless, the distance that goods could be carried was strictly limited by the weight that the human back could bear. On the farm, ropes of plaited straw, rushes, or horse-hair were used for carrying large bundles of hay or straw from the rickyard to the sheds housing the animals. Deep baskets

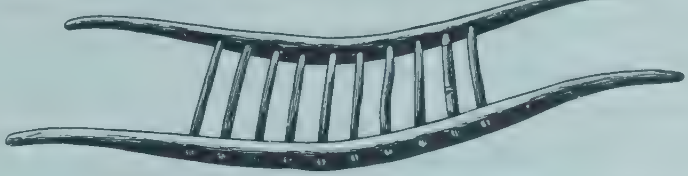

FIGURE 79—*Hand-barrow from Glamorganshire, 184 in long by 65 in wide.*

for women to carry peat from the bog to the farm may still be found in Ireland. These burden-creels, as they are called, were slung from the shoulders like a rucksack, leaving the hands of the carrier free for knitting as she walked along. In the Isle of Man burden-creels were generally suspended from a strap passing round the carrier's forehead.

A slightly more advanced aid in carrying material for short distances was the hand-barrow (figure 79). This was made from two parallel pieces of wood joined together by a number of cross-pieces, which formed the carrying-surface of the barrow. The side-pieces were extended to form handles. As recently as 1850, in Merionethshire, manure was carried to the fields upon these barrows. Each farm in a locality specified a day for dung-carrying, and all the neighbours would congregate at the chosen farm with their barrows. The carrying was performed by means of a shuttle-service, the load changing hands many times before it finally reached the field.

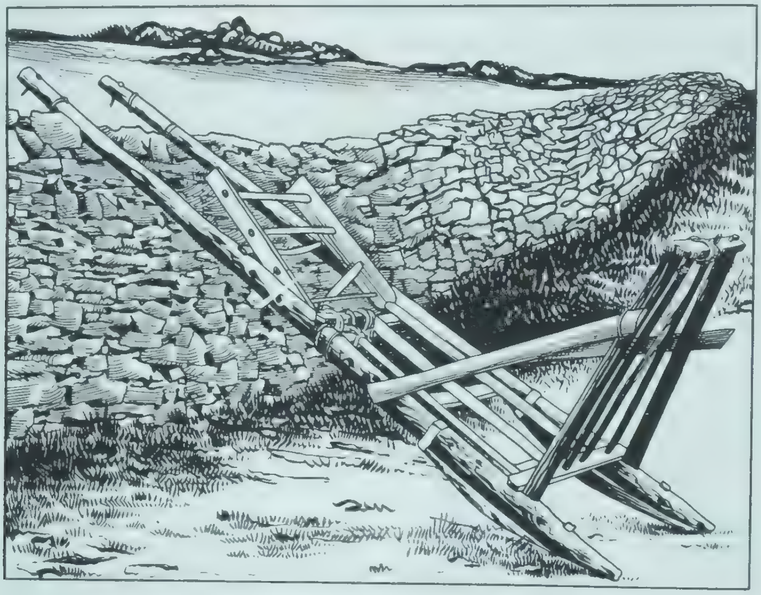

FIGURE 80—*Dorsal-car from Blaencorrwg, Glamorganshire.*

Wheel-less sledges were also very common in hilly districts, where they were mainly used for short-distance porterage around the farm. In the British Isles they persisted until recent times in Cornwall and Devon, Wales, Cumbria, Scotland, and Ireland, as well as in the marshy districts of East Anglia. Sledges were of two types, the dorsal-car and the slide-car.

The dorsal-car (figure 80) consisted of two stout, parallel timbers joined together by a number of cross-bars. The side-pieces extended to form a pair of shafts, which were attached to the horse high up on the collar. The vehicle was dragged along the ground at a tilt, hence it was necessary to fit a wooden framework, or ladder, at the back, so that the load would not fall out. A smaller ladder was also fitted at the front, while the load could be made more secure by tying it down with ropes—a necessary procedure when carrying hay, corn, or wood on steep mountain slopes.

The slide-car (figure 81) differed from the dorsal-car in that the whole base of the vehicle was dragged along the ground like a sledge. Again it consisted of two parallel side-pieces joined by a number of cross-bars that formed the carrying-surface of the car. While the dorsal-car was dragged, with the end of the side-pieces bearing on the ground, the slide-car was equipped with a pair of wooden runners bearing the weight of the vehicle. Generally the body was tilted forwards on these runners, the angle of tilt depending on the slope of the land on which it was used. The vehicle was attached to the horse by a pair of trace-chains rather than by shafts.

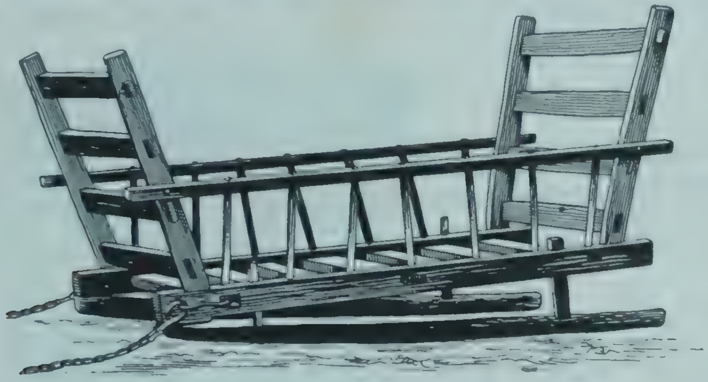

FIGURE 81—*Slide-car from Llanbrynmair, Montgomeryshire.*

These forms of transport, well known from very early times (see vol I, ch 26, and II, ch 15), are still occasionally used in upland districts. They are extremely suitable for the topography of such areas, while the fact that they can be made by the farmer himself, from timber growing on the farm, accounts in no small measure for their continued use. Upland farming is generally difficult and, since the income of the individual farmer is low, tools and implements are consequently primitive and specialized craftsmen rare.

While human porterage and sledge-transport was efficient for short-distance carriage, something more adaptable was required for longer distances. Pack-horse teams, common in medieval times, continued to be used in hilly districts; for example, they were very common in Devon and Cornwall until the end of the nineteenth century. In those counties they were used not only for long-distance transport but for carriage around the farm. Pack-horses were equipped with a pair of baskets (panniers) for carrying peat and similar material; or with a pair of boxes (pots) for dung-carrying; or with a pair of wooden frames (crooks) for harvesting. All these were slung over the animals' backs. In addition, pack-horses were sometimes equipped with an arched wooden saddle, the load being usually in a bag slung over it.

Carts. In medieval times two-wheeled carts were in general use wherever the terrain was suitable for wheeled transport. The carts were either drawn by horses, as seen in the illustration from the Luttrell psalter (vol II, figure 500), or by teams of oxen, and were equipped either with spoked wheels or with primitive solid-disk wheels. Vehicles with solid wheels remained common in many parts of the world until recently, and may still be seen in a number of isolated districts. In early nineteenth-century northern Scotland heavy carts with tripartite disk-wheels were numerous, although they were being gradually supplanted by lighter carts designed to be drawn by a single horse. The wheels of the old heavy carts turned in one piece with the axles, and because the vehicles tumbled along they were known as 'tumblers'.

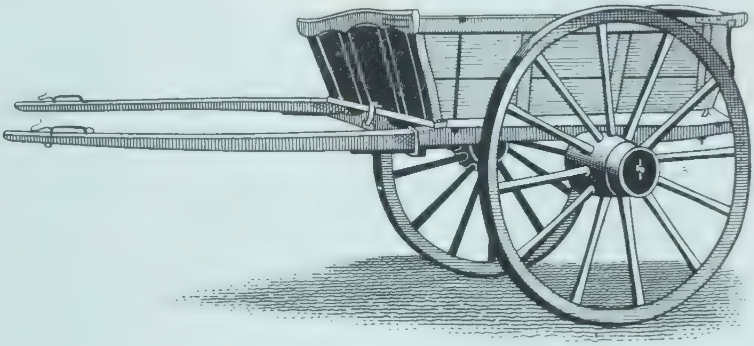

FIGURE 82—*Scotch cart, 1813.*

The Lowlands of central Scotland were, however, the centre of a great agrarian movement in the late eighteenth and early nineteenth centuries. English farmers sent their sons as farm-pupils to Scotland, where the most advanced and skilful husbandry was thought to be practised. In that region the design of carts and agricultural implements generally was far in advance of anything then used in other parts of Britain. Through contacts between England and Scotland, the Scotch cart was copied by craftsmen not only throughout Britain, but on the continent as well. It was generally light enough to be pulled by one horse (figure 82), in spite of its long capacious body. A typical cart measured 5 ft 6 inches in length, 4 ft 6 inches in width, and 1 ft 7 in deep at the front. The narrow spoked wheels had a diameter of between 4 ft 6 in and 4 ft 10 in. The body was often made to tip, in which case the cart was known as a coup-cart. The Scotch cart was therefore a general-purpose farm-vehicle, for when it was required for harvesting a wooden framework could be attached to the top of the body, thus considerably increasing its load-carrying capacity. Throughout the nineteenth century one-horse carts of Scottish design replaced the traditional heavy vehicles on the English farm.

The Luttrell psalter of the fourteenth century shows the heavy two-wheeled vehicle in general use in England in the Middle Ages. It was drawn by three horses in tandem, and the massive six-spoked wheels were fitted with iron lugs to prevent the vehicle from slipping. The sides of the cart were open rather than boarded, while fore- and tail-ladders were fitted to take the overhanging load. Until the introduction of the Scotch cart in the late eighteenth century, English two-wheeled carts followed this medieval tradition. They continued to be heavy and clumsy, and required at least two horses, or four oxen, to draw them. In marshy districts the wheels were not even shod with metal, while in other districts crescent-shaped pieces of iron, called strakes, were nailed to the wheel to prevent wear. One very important development on the English midland plain, however, was that at some time during the seventeenth and eighteenth centuries four-wheeled wagons replaced the traditional harvest-cart, especially on the larger farms. On the smaller farms two-wheeled vehicles with open sides and fore- and tail-ladders continued in use until fairly recent times. Although these carts were generally light, they were very much in the medieval tradition.

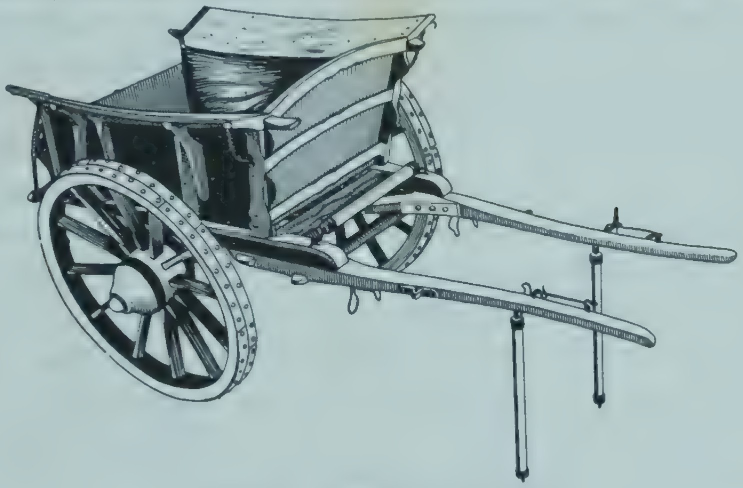

FIGURE 83—*Tumbril from north Essex.*

While four-wheeled wagons were used for harvesting on the English plain and the flatter regions of Europe generally, two-wheeled carts of small capacity were retained for special purposes on the farm. For dung-carting two-wheeled vehicles were invariably used. As early as the mid-eighteenth century, tilt-carts or tumbrils were in use throughout western Europe (figure 83). A tumbril had fairly low wheels, and a body sloping upwards to a very high frontboard, which leaned out over the horse's back. Two heavy pieces of oak formed the frame of the cart, and these projected at the back to rest on the ground when the cart was tipped for unloading. An older version of the tumbril was the box-cart with a fixed body that could not be tipped. Its general shape was that of a tumbril, but in order to unload it the horse was unharnessed and the whole vehicle, including the shafts, tipped backwards.

In the hilly districts of Europe, where slopes were too steep for the use of wagons yet not so steep as wholly to forbid wheeled transport, two-wheeled carts were used for all farming purposes, including harvesting. Although box-carts were often adapted for harvesting by the addition of frames at the top, specialized harvest-carts were nevertheless common. The simplest of these was the cart consisting of a flat wooden platform placed on a pair of wheels. The Cornish wain of the eighteenth century and possibly earlier was of this type—a long rectangular platform with arched guards over the low wheels. It had fore- and tail-ladders, while at the back there was a small windlass for tightening the ropes thrown over the load. The Scottish harvest-cart was similar in shape and design, though slightly smaller, while the Welsh *gambo* differed in that it had a pair of rails to prevent the load spilling over the wheels, rather than arched wheel-guards. These Celtic harvest vehicles pulled by either horses or oxen may be regarded as the British equivalents to the Mediterranean ox-carts.

In Scandinavia and north-western Europe generally, the normal harvest-cart was rather different. It had a very long, narrow, rectangular frame. A number of wooden spindles, each approximately 12 in long, was fixed to the frame at such an angle that the spindles overhung the two wheels. The wheels were generally very low, while the cart was again fitted with fore- and tail-ladders.

Wagons. It is not known at what date four-wheeled wagons were introduced into Britain, but it is almost certain that they were extremely rare until the sixteenth century. In the Middle Ages the lack of contact between one region and another, and the communal nature of farming, meant that elaborate wheeled vehicles were unnecessary and rare. The long wagon with its canvas cover, illustrated in the Luttrell psalter, was without doubt a vehicle for carrying people rather than goods: a successor of the Roman *carruca* (vol II, p 540) rather than a predecessor of the carrier's wagon. Four-wheeled vehicles were, however, in general use on the continent of Europe in the Middle Ages, and haulage firms competed to some extent on the main routes. For the limited amount of long-distance transport on English medieval roads two-wheeled vehicles carrying no more than a ton were used. The sixteenth century saw the break-down of the localism of the Middle Ages, which meant that more and better vehicles were required to transport the produce of the agricultural regions to the ever-growing towns. The four-wheeled carrier's wagon became very common in the late sixteenth century, and although at that time the largest wagons carried only four tons, by the end of the seventeenth century wagons able to carry anything up to eight tons were numerous. These large vehicles, each drawn by a team of up to twelve horses, ran on certain routes on days specified beforehand. For example, there was a regular service between some Sussex towns and London, the wagons taking loads of wheat and oats to the metropolis. For the return journey to Sussex they loaded up with old, but sound, ships' timber from London ship-breaking yards. This timber was bought by Sussex landowners for use in building cottages and barns on their estates.

The old stage-wagons were well suited for long-distance haulage, but owing to their great weight they were unsuitable for transport around the farm. During the mid-eighteenth century, the whole aspect of British farming was changing very quickly. More than two hundred private enclosure acts were passed between 1727 and 1760, and enclosed farming became the rule rather than the exception. With this release of initiative, there arose a demand for something much larger than the two-wheeled carts hitherto used on English farms. Village wainwrights took as their model the existing stage-wagons, and adapted them to their needs. Three- or four-ton wagons became the rule; loaded with hay or corn-sheaves, they could easily be drawn by two horses on the journey from the fields to the rickyard.

The general principle on which wagons were built was uniform throughout the country, despite much variation in detail. Counties and districts favoured their own particular designs, the differences being due to the varying demands of soil and topography. For example, the wagons of East Anglia were heavy and box-like, as befitted an area of flat land with large fields. The wagons of the Cotswolds, on the other hand, in use in an undulating region with numerous steep slopes, were much lighter, and excess weight was cut down wherever possible. In general, English farm-wagons may be divided into two distinct types —the box- and the bow-wagon. The box-wagon, as it name suggests, had a deep rectangular body, and where raves or side-boards occurred they were generally narrow (figure 84). This type of vehicle occurred in eastern England, the Midlands, the Welsh border counties, and in south-eastern England.

The bow-wagon had a much shallower body, characterized by side-boards arching over the rear wheels. This lowered the bed of the wagon, without lessening the diameter of the wheels. The bow-wagon was common to the west of England, occurring from the Chilterns in the east to Glamorganshire and Devon in the west.

In general design the wagons of Lincolnshire, resembling those used in the Low Countries and western Europe generally, may be regarded as the simplest of English box-wagons. The typical Lincolnshire wagon was a large vehicle characterized by a deep body, which measured 27 inches in depth at the back, 24 inches in the centre, and 38 in at the front. The lofty, sloping front-board was usually elaborately decorated, and the name of the owner, his address, and the date of manufacture were written on it. Although the body was generally narrow, measuring no more than 42 in wide, it had the considerable length of 12 ft 6 in. The sides of the vehicle were characterized by a large number of wooden pins or spindles acting as supports for the sides, while the bottom frames of the body were notched to form a waist. On turning the wagon, the wheels would enter the waist, and the lock was therefore considerable. The wheels themselves were greatly dished and large, the hind wheels with a diameter of 65 in and the front wheels with a diameter of 54 in. The wagon was not usually equipped with side-boards, thus resembling the continental vehicles, but a wooden framework could be fitted on it to take any overhanging load.

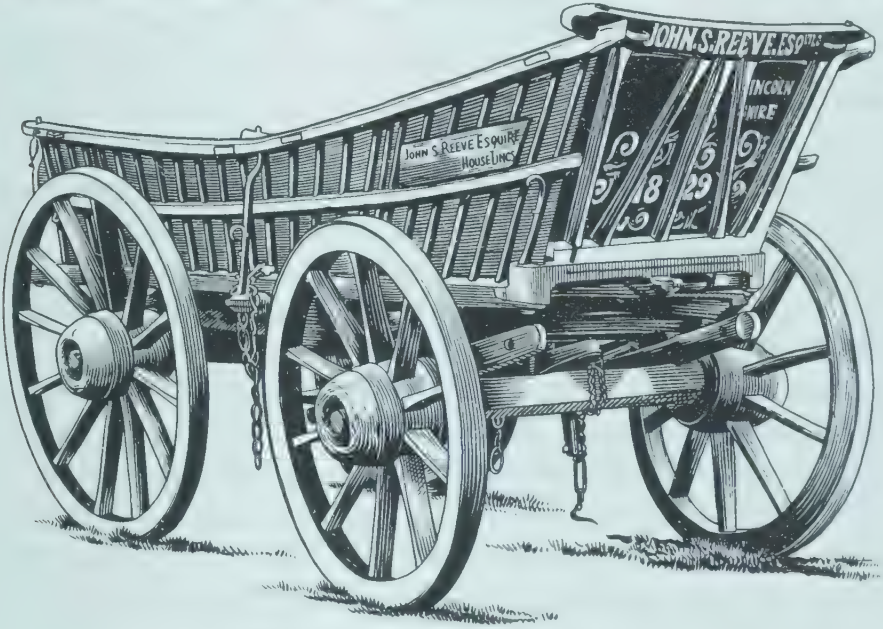

FIGURE 84—*Box-wagon from Lincolnshire.*

The Wiltshire wagon was probably the parent type of all the west of England bow-wagons, for although in shape it was similar to those used in the Cotswolds, Oxfordshire, and Glamorganshire it was much simpler in design. Wagons from the south of the county had narrow-tired wheels for use on the hard chalk-land of Salisbury Plain, while those from the north of the county had broad wheels, up to 8 inches in width, for the clay land of the vale of Pewsey and the vale of the White Horse. Apart from this variation in the width of wheels, the wagons used throughout the county were remarkably uniform in design. The outstanding features of the Wiltshire wagon were the wide side-boards that curved archwise over the rear wheels. These boards are never found on continental vehicles. Since the bottom frames of the body were straight, the Wiltshire wagon suffered one great disadvantage, in that it required as much as a quarter of an acre to turn in, for the wheels soon rubbed against the frames if the vehicle was turned too sharply. The typical Wiltshire wagon had a very shallow body, no more than 15 in deep. On the other hand, the body was as much as 80 inches in maximum width, and 12 ft 6 in long. Although the actual body of the vehicle was small, the overhanging side-boards added considerably to its load-carrying capacity. The wheels were generally smaller than those of the box-wagon, the hind wheels of the average wagon having a diameter of 55 in and the front wheels of 45 in (figure 85).

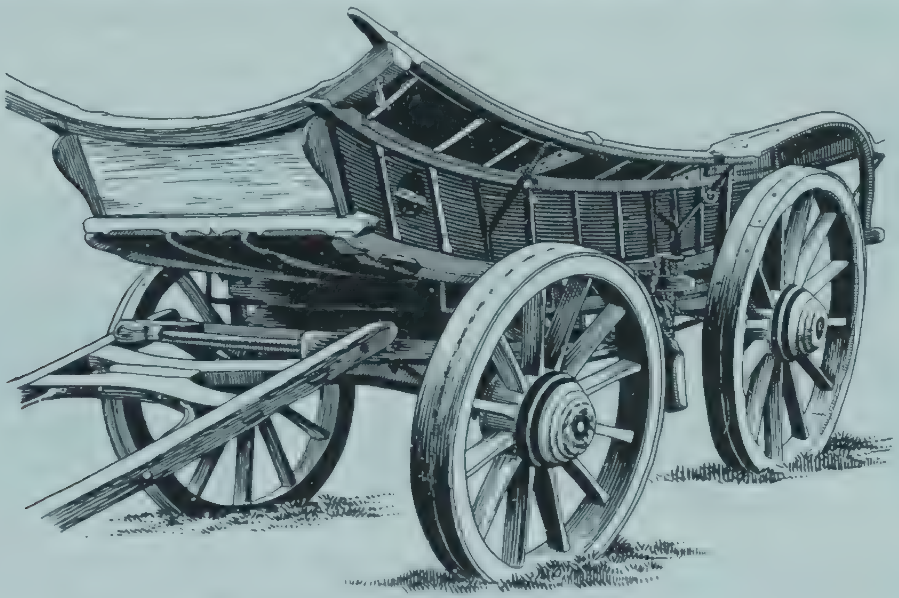

FIGURE 85—*Bow-wagon from Wiltshire.*

All the early farm-wagons were designed for a specific type of soil and country, and were built by village craftsmen who followed traditional methods and designs. In this way distinctly regional styles of wagons came into existence. It was not until the late nineteenth century that standardized vehicles produced by large-scale manufacturers came on the market, and these boat-wagons and trolleys with smaller wheels, greater lock, and sprung undercarriages were used alongside the older village-made vehicles.

III. HARNESS

Information about the history of harness between 1500 and 1900 is very scarce, but the harness now in use has altered little since 1800 (figure 86). Harness varies according to the size and type of horse employed and the work to be done.

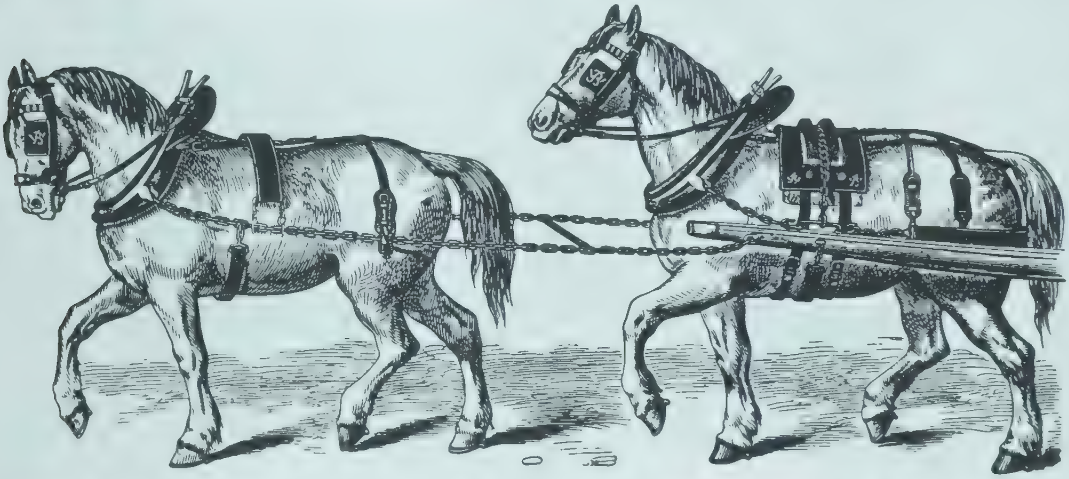

FIGURE 86—*Two cart-horses wearing harness as illustrated in a nineteenth-century trade catalogue. The shaft-horse has full cart-harness, but the trace-horse wears only a collar, hames, bridle, and three straps.*

Different tasks, such as carting and ploughing, require different harness: the horses wear full shaft-harness when carting and trace-harness when ploughing. To be fully equipped, a shaft-horse requires a collar, together with hames, saddle, breeching- or back-band, and a bridle. For ploughing only a collar, hames, bridle, and back-band are necessary.

The collar is an indispensable feature of all types of draught harness. Yokes connected to a cart or plough by a long pole called a neb were used when the ox was the common draught-animal on the farm, but even oxen came to be harnessed with collars and hames before they were finally superseded by horses for ploughing and carting (vol II, ch 15). Light wooden hames were used, with a very pronounced curvature to fit the broad neck of an ox.

A horse works by pushing against its collar, and a good collar provides the means of giving a steady draught. Horses used in hilly districts require light collars of close fit because of varied gradients and uncertain draught. The Liverpool collar, common in the northern counties, fits more closely than the collar of midland design, used in flatter land, and is less heavy and thick. Collars normally consist of a stiff leather tube stuffed with straw, but a few early rush-covered collars are in existence. This tube is known as the wale. The main body of the collar is also made of straw, covered with woollen cloth. Collars carry the heavy wooden or metal hames to the hooks of which the trace-chains are attached for drawing the cart or implement. In cart-harness, chains from the shafts also pass over a wooden saddle padded underneath with felt or straw.

Each leather strap in cart-harness supplementary to the collar and saddle has a special name. From the saddle the girth or belly-band goes under the horse to prevent the shafts from rising. The breeching- or back-band is slung across the horse's rump by breeching-straps from the back. The breeching-band is secured to the shafts sufficiently closely to take the forward draught of a cart going down hill and keep it back. From the horse's tail to the cart-saddle a wide strap known as the crupper extends, and between the animal's legs hangs a martingale fastened to the collar and belly-band.

Reins pass over the horse's back and saddle through the hames and are attached to a bit in the mouth. The bridle worn on the head consists of a head-stall, brow-band below the ears, nose-band, and blinkers which limit the range of vision.

Decorative harness was used for cart-horses in town and country throughout the nineteenth century, and was particularly important between 1850 and 1900. Brasses of traditional design were fastened to the martingale, blinkers, and face-piece. As well as brasses some horses wore on their heads disks of brass swinging in brass rings, or plumes of red, white, and blue mounted on brass and known as fly-terrets. Team- or latten-bells fixed in a leather hood above the collar, and often fringed with red wool, gave warning of the approach of a horse and cart. Housen or housings, which were often made in a semicircular shape decorated with brass mountings or painted figures, would be attached to the top of the collar. Wooden housen were used in the eighteenth century, but leather became more common after 1800. This form of decoration has, in common with other trappings, now gone out of use.

The editors and authors desire to thank Mr J. W. Y. Higgs, Keeper of the Museum of English Rural Life, Reading, for his assistance in the preparation of this chapter.

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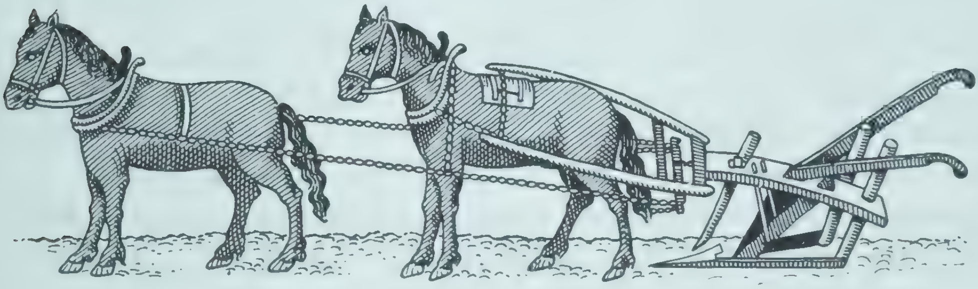

Jethro Tull's hoe-plough, showing the method of harnessing the horses to it. 1733.

7

SPINNING AND WEAVING

R. PATTERSON

I. FIBRES AND THEIR PREPARATION

THE period from 1500 to 1760 is one of the most important in the history of textile manufacture in Europe. The profound effects of the Renaissance were reflected in changing aspirations and higher standards of living, while the spirit of adventure and commercial enterprise led to great expansion of trade in newly developed markets.

Textiles, particularly wool, linen, and silk, were closely linked with vicissitudes in the wealth of nations, and regulation of their manufacture and sale was fundamental to the economic policies of the new nation-states. The religious upheavals of the Reformation and Counter-reformation divided nations and scattered their populations, and amidst international and civil wars the preponderance of power shifted rapidly. A flourishing textile trade was often the basis of national greatness: Spain had a flourishing textile industry in the sixteenth century, when the German trade also was at its height. Holland attained her Golden Age in the seventeenth century, to be followed by Britain's supremacy of the eighteenth and nineteenth centuries.

As the power of the guilds waned the state assumed control of the textile manufactures, regulating each process strictly, safeguarding supplies of materials, and protecting the home market. Spinning-schools were set up in many European countries to foster the trade, and in Scotland a spinning-wheel was presented to each proficient student. Many strange enactments appeared, as in Silesia, where no farm-worker, male or female, was permitted to marry until able to spin. In England from 1666 to 1786 it was unlawful to bury a corpse in anything but wool, whereas the Scots were prescribed the use of linen for their shrouds.

This period saw the firm establishment of the factory system in Europe. At the beginning of the sixteenth century John Winchcombe had a factory at Newbury, Berkshire, thus described by Thomas Deloney:

> Within one room being large and long
> There stood two hundred looms full strong . . .

And in another place hard by
An hundred women merrily
Were carding hard with joyful cheer
Who singing sate with voices clear
And in a chamber close beside
Two hundred maidens did abide . . .
These pretty maids did never lin [cease]
But in that place all day did spin . . . [1]

This factory embraced all the processes of woollen-manufacture. Similar factories were set up before 1550 at Malmesbury, Burford, Lavenham, Newbury, Cirencester, Bath, Halifax, Manchester, and Kendal, but the anti-factory legislation of 1555 attempted to restrict country clothiers to one loom. The seventeenth century saw Colbert's model factory under the management of Van Robais at Abbeville, where 1692 workers were employed, but it was in the second half of the eighteenth century that factories became essential for the application of the new textile machinery.

Sheep's wool, the fibre of greatest economic importance, continued to take pride of place in clothing. The improvement and great increase of the Spanish merino flocks in the sixteenth century produced the finest wools of commerce. The finest Spanish wool came from Segovia, with slightly inferior qualities from Castile, Estramadura, and Andalusia [2]. English wools were considered next in order of fineness, followed by the French wools of Languedoc and Berri. Of the English wools the most expensive came from Norfolk, Suffolk, Sussex, and Herefordshire, second grades from Essex, Wiltshire, Dorset, Somerset, and Gloucestershire, third grades from Cambridge, Kent, Hampshire, Devon, Cornwall, Northumberland, Hertfordshire, and Leicestershire, and the coarsest from Yorkshire, Westmorland, Cumberland, and Lincolnshire [3]. Welsh and Irish wools were coarse, and Scottish wools were unpopular owing to the tar frequently smeared on the sheep as a protection against the weather. The export of English wool was prohibited by statute from 1660 to 1825.

The sheep were shorn with hand-shears unchanged in design since the Middle Ages (vol II, figure 154), the fleece being removed in a single piece and sorted into qualities. In Spain the loins and skirts were removed and the remainder divided into three qualities of descending fineness known as firsts, seconds, and thirds. The quantity of each grade was in the ratio of 12:2:1 [2]. French wools were divided into high wool of long staple and low wool of short staple. In England the fleece was divided into three grades: mother-wool from the back and neck, the wool of the tail and legs, and the wool from the breast and belly.

The fleeces were of three types: (i) finest wool, used for woollens and comprising the majority of English fleeces; (ii) longer pile, used for worsteds; and (iii) medium length, used in the hosiery trade.

Before processing, the wool was washed in a mixture of three parts water to one part of urine, to remove grease and salts, and rinsed in running water, often in a basket attached to a captive raft. The washed wool was dried on a frame in the shade and beaten with sticks on a hurdle or on a framework of cords to open the texture, and was then ready for carding, bowing, or combing. In 1733 John Kay invented a machine for beating wool with spring-loaded laths raised by tappets on a wheel [4].

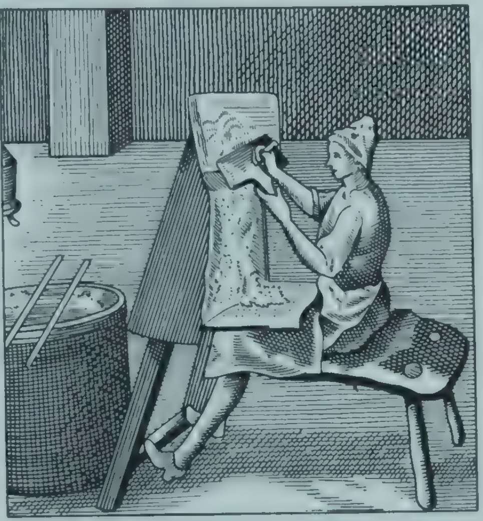
FIGURE 87—*Carding wool. From an early eighteenth-century engraving.*

In *carding* the short wool-fibres destined for woollen yarn, hand-cards almost exactly of the medieval type (vol II, figure 167) were employed. The three operations of working the fibres into an even layer, stripping from one card to the other, and doffing the loosened fibres in the form of a spongy sliver were followed as in earlier times. To increase the output the cards were made much larger and one of them was mounted at an angle on the end of a bench (figure 87). With this stock-card fixed the carder could use both hands on the free card, which was frequently suspended from the ceiling and balanced by a counter-weight. Stock-carding was often a preparatory loosening process preceding hand-carding. Wool was prepared for carding by sprinkling with olive-oil in the proportion of 1 part of oil to 5 of wool for the weft and 1 part of oil to 9 parts of wool for the warp. Butter was often used instead of oil.

The advent of mechanical spinning foreshadowed by Lewis Paul in 1738 (p 162) led the same inventor to design two carding-machines ten years later [5]. The first was in effect a large stock-card, 3 ft by 2 ft, with the card-clothing attached in parallel strips (figure 88). This was mounted horizontally on a vertical shaft and could be rotated by a foot-lever for stripping. The free card was fitted with two handles, for manual use. The carded slivers, removed with a long needle-comb, were joined end-to-end to make a continuous length which was wound on a cylinder by means of a tape.

In Paul's second machine the card-clothing was attached in strips to the

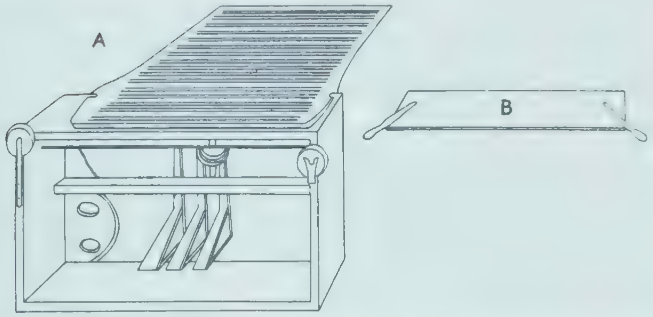

FIGURE 88—*Lewis Paul's rectangular carding machine, 1748. The fibres were placed on the 3 × 2 ft card* (A) *and worked with the hand-card* (B). *The roll was stripped off after turning* A *through 180° by means of the treadles, and wound over a ribbon passing over the two pulleys at the front.*

surface of a cylinder turned by hand (figure 89). The cylinder worked against a concave board lined with card-clothing which could be lowered and rotated for stripping. The process was still intermittent and the separate cardings, removed with a comb as before, had to be joined together.

A more advanced form of carding-machine was patented earlier in 1748 by Daniel Bourn of Leominster [6]. This was a rotary machine in which four card-covered cylinders driven by hand or water-wheel worked against each other (figure 90). The distance between the cylinders was adjustable, and two of the four cylinders had an automatic reciprocating motion along their axes to distribute the fibres evenly over the surfaces. No working details are given, but the doffing would no doubt have been effected with a long comb.

Although not successful this machine was the prototype of later roller carding-machines.

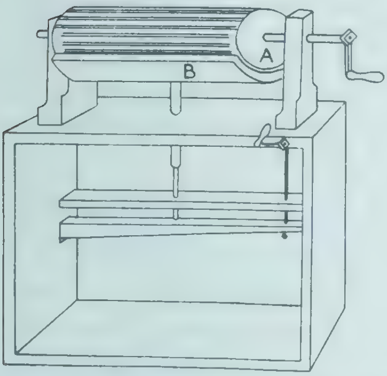

FIGURE 89—*Paul's revolving carding-machine, 1748.* A *is the cylinder covered with strips of card-clothing,* B *a concave card completely covered. To strip off the carded fibres the cylinder was lowered and turned through 180°.*

The *bowing* of wool and cotton (vol II, p 195), as an alternative to carding or in preparation for it, continued to be practised, especially in felt manufacture or where wire cards were not readily obtainable. The bow increased in dimensions and was usually suspended from above. The gut of the 6-ft-long bow was plucked with a piece of wood and the vibrating string passed among the entangled fibres to loosen them and remove small impurities.

Combing of long-staple wool was performed by hand throughout the period. It was essential for the production of worsted yarn, which requires

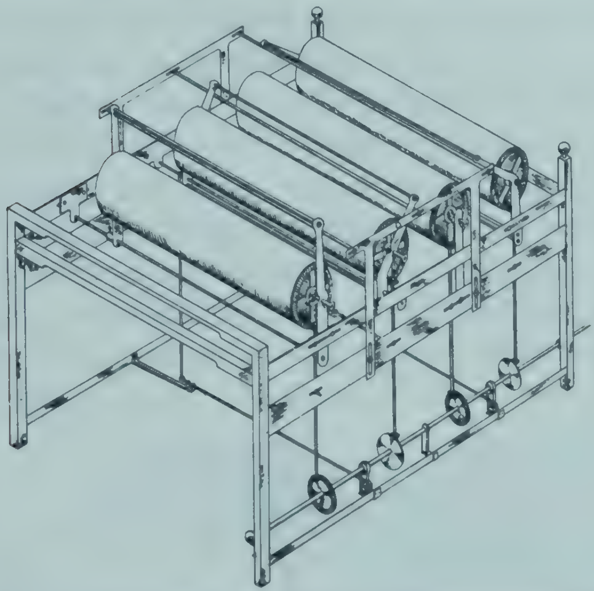

FIGURE 90—*Bourn's carding machine, 1748. The fibres are carded between pairs of rollers rotated in opposite directions by water-power through the shafts and gears.*

parallel fibres from which the shortest ones have been removed. The combs remained almost unchanged, consisting of two or three rows of long, tapering, steel teeth mounted in horn on a wooden handle. They were heated over a stove and attached to a hook on a vertical post (figure 91). The wool, previously soaked in soapy water and wrung out with a winch, was oiled with butter, olive-oil, or colza-oil. Spanish wool which had been washed on the sheep was merely dipped in hot soapy water and combed without being oiled [2]. About 2 oz of wool were attached to the teeth of one comb and worked with the other. The combing, beginning at the tips of the fibres and penetrating deeper at each stroke, was continued until the wool was transferred to the second comb, when the combs were reversed and the process was repeated. The wool was pulled off the comb in a long sliver, and sometimes this was gently recombed with cooler combs before being coiled into a 'top'. The short fibres or noils remaining on the comb were utilized in blanket manufacture.

The teeth were kept very sharp and

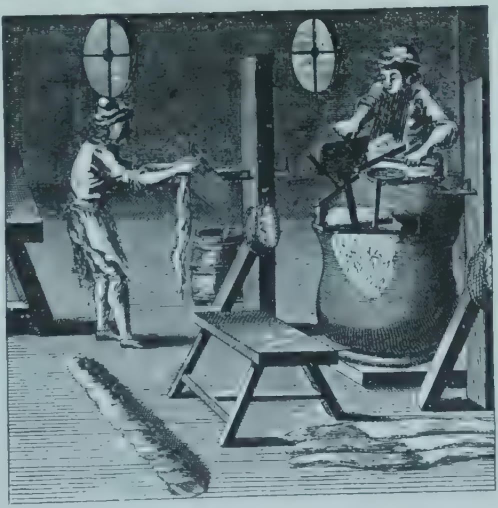

FIGURE 91—*Combing wool. From an eighteenth-century engraving.*

were straightened when necessary with a brass tube. A wool-comber could comb about 28 lb of wool a day, and the successful mechanization of this process remained beyond inventors' skill until the nineteenth century.

Flax. The cultivation of flax changed very little during many centuries, but greater care was taken in preparing the ground and selecting the seed. In Holland it was usual to sow seed from heavy soils on light soil and vice versa, although it was found economical in Ireland to use seed taken from the first crop for sowing a second. To obtain fine linen for the extremely delicate cambrics of northern France, the seed was sown thickly and the growing crop was drawn up and sheltered from wind and sun by laying over it branches supported on stakes.

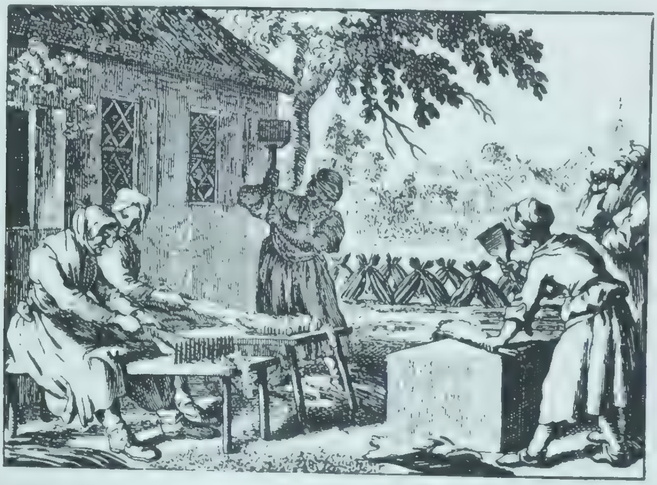

FIGURE 92—*Flax-working.* (Left to right) *Combing the stalks through a ripple; hackling, working the stalks with mallet and scutcher. From an engraving by D. Chodowiecki (1726–1801).*

The flax was pulled before the seed was fully ripe, to preserve its suppleness of fibre. It was laid on the grass, as in Holland, or tied into sheaves and stooked, as in Ireland, for 3 or 4 days to permit ripening of the seeds. The seed-capsules were then removed by drawing bundles of flax through a long coarse comb or 'ripple' (figure 92). This ripple was often mounted on a bench.

The retting process was conditioned by the availability of ponds, lakes, or rivers; ditches and pits were often dug for the purpose. After retting for 1 to 2 weeks the flax was spread out on short grass for 3 to 6 days for partial drying and bleaching and to allow the dew to complete the retting. Dew-retting without steeping was employed in parts of Russia, Germany, and America, but required 3 or 4 weeks to complete the fermentation, while snow-retting in Russia and Sweden lasted through the duration of the snows. In Germany the finest flax was steeped 4 or 5 days in warm diluted milk, and elsewhere lye of wood-ashes and other chemical agents were employed. Steeping unripe flax was a speedy method practised to a large extent in Belgium.

The retted and grassed flax was usually dried artificially. In Holland, specially built ovens were heated to such a temperature that a person inside would not feel uneasy. In Ireland the flax was laid on hurdles over a fire, with resultant unequal drying, discoloration by smoke, and great risk of loss. The drying of flax in domestic ovens was frequently forbidden owing to the fire-hazard.

When dry the flax was ready for braking. The Dutch brake was widely adopted throughout Europe, being fitted with two or three bars to break up the woody stalk or boon. Attempts were made by Abraham Hill in 1664 and by Charles Moreton and Samuel Weale in 1692 to mechanize flax-dressing processes [7]. In 1727 a Scot, David Donald, invented a roller mechanism for beating and scutching flax, and in the following year the machine, driven by a water-wheel, was functioning successfully in Fife. James Spalding invented a machine for dressing flax in 1728, from ideas he gained during a visit to Holland. Similar machines were introduced into Ireland [8] and comprised a horizontal fluted roller engaging with similar rollers above and below (figure 93). The flax was drawn inwards between the two upper rollers and emerged between the two lower ones, the process being repeated until the boon (woody portion) was sufficiently broken.

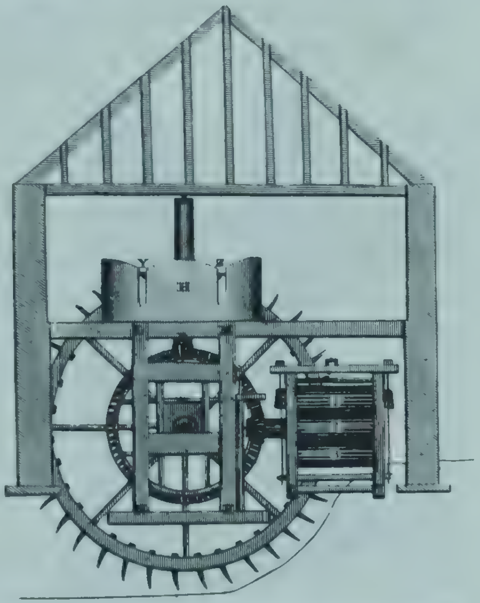

FIGURE 93—*Flax-breaking machine with scutcher* (H) *above.* (Y, Z) *Holes for inserting broken flax to be scutched;* (1, 2, 3) *rolls for breaking the flax.*

The broken boon was removed by striking the flax over the edge of a board with a rectangular scutching-blade (vol II, figure 158). If the blade struck the flax over the board it damaged the fibres, but the Dutch scutching-board, with a notch in one side to take the flax, eliminated this danger.

Machinery for scutching was introduced in the early eighteenth century; the usual form in Scotland and Ireland was a vertical axle with four projecting arms that rotated in a horizontal drum (figure 93). The flax was inserted through slits in the top and side of this drum and the arms reproduced the action of the scutching-blade and removed the boon.

In Scotland, Ireland, and elsewhere the fibres were then beaten with a ribbed mallet on a block of wood to soften them (figure 92), but in Holland a fining-mill was employed before 1736 (figure 94). This machine was worked by wind, horses, water, or hand, and consisted of a slotted shaft between two wooden uprights, encircled by eight removable spindles. In use, the flax fibres were inserted in bundles through the slotted shafts and then turned alternately backwards and forwards for two revolutions each way. The machine held about 6 lb of flax and as the mass turned back and forth the fibres rubbed against the spindles and were separated into fine filaments. About eighty double turns each way produced the desired effect.

The fibres were finally separated by drawing bundles of flax through a fixed comb or hackle (figure 92). One end was combed and then the other, and the process was repeated with hackles of finer teeth. The Scottish hackles were fitted with stout brass teeth, but in 1728 English and Dutch hackles with long steel teeth were introduced. Hackling was a delicate operation since breakage of the fibres had to be avoided; women were usually employed for the purpose. The short, waste fibres were known as 'tow' and the long, prepared fibres as 'line'. The tow was carded and spun like wool or cotton and made into smocks, underwear, and bedclothes for everyday use, while the waste from scutching was used to make sack-cloth.

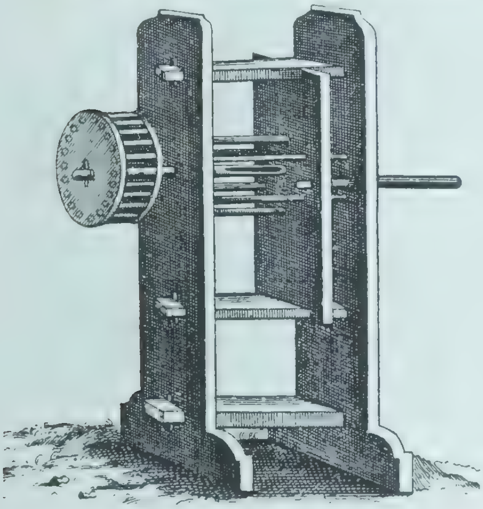

FIGURE 94—*Dutch fining-mill, c 1735. The flax was inserted in the eye of the central shaft.*

In Holland the braking and scutching processes occupied about 3 months, and one workman could treat 20 lb of flax a day.

The seed, if required for sowing, was separated from the boll by trampling with horses on a barn floor, and finally the husks were removed with a winnowing machine as used for corn.

Hemp also was widely cultivated, particularly in Italy, Germany, Holland, and later in Russia, as a substitute for flax but especially for the manufacture of sails and cordage.

The hemp plant (*Cannabis sativa* L) normally grows to a height of 6 ft, but in some regions up to 16 or even 20 ft. The plants were pulled and retted in standing water for 15 days, after which the bundles were dried. In sixteenth-century Italy the fibres were then separated by hand and passed between fluted rollers before being beaten with mallets and hackled as for flax. A hemp-stamping machine patented in 1721 by Henry Browne comprised vertical timbers which were raised and dropped by tappets on an axle turned by hand, wind, water, or horse power [9].

The *cotton* plant (*Gossypium* spp) occurs in many forms. Linnaeus in 1753 enumerated five distinct species:

1. *Gossypium herbaceum*
2. ,, *arboreum*
3. ,, *hirsutum*
4. ,, *religiosum*
5. ,, *barbadense*

The first is a herbaceous annual growing to a height of 18 to 24 in. It is cultivated in India, China, eastern Mediterranean countries, southern Europe, and North America, and is economically the most important. The second species is a tree attaining a height of 12 to 20 ft. This perennial form is found in Asia, north Africa, and parts of America. The remaining three species are all shrubs varying in height from 2 to 10 ft and are perennial in the hottest countries and annual in the cooler climates. They are found in Asia, Africa, and Central and South America.

Until the eighteenth century cotton was imported into Europe principally from Cyprus, Smyrna, Acre, and Syria. Cotton thread was obtained from Damascus, Jerusalem, and India, the finest being produced in the coastal area of Bengal. During the first half of the eighteenth century cotton of fine quality, known as cotton of Siam because of the origin of the seed, was imported from the West Indies, and before the end of the century West Indian cotton was the main source of England's supply. An unsuccessful attempt was made to grow cotton in Provence at the end of the sixteenth century.

At the opening of that century the weaving of cotton fabrics, and particularly of mixed cotton and linen fustians, was firmly established in Italy, Switzerland, Germany, and Flanders. At this time the fustian industry was reviving in France and was beginning to expand into Holland. Although attempts were made to weave fustians in England with cotton from the Levant in 1430 the first definite mention of a cotton industry there is of about 1621 in Lancashire [10], where it was probably introduced by Flemish immigrants after the fall of Antwerp in 1585.

The large-scale importation of Indian cotton goods by the Dutch and English East India Companies led to the prohibition of such imports in England in 1700, and in many other European countries later, for they were thought to compete with local manufactures. From 1720 to 1774 the weaving of pure cotton calicoes was forbidden in England.

Cotton was picked by hand and passed between two rollers to separate the seed from the fibres. The cotton-gin in India was turned by hand, but in the West Indies a foot-treadle was incorporated, and one workman could separate up to 60 lb a day. The cotton was tightly packed by treading into wet bags of coarse cloth 9 ft high and 4 ft wide, which held about 300 lb each [2]. Before being carded or bowed as with wool, the cotton from the bale had to be loosened thoroughly by beating with sticks on a hurdle or wire frame.

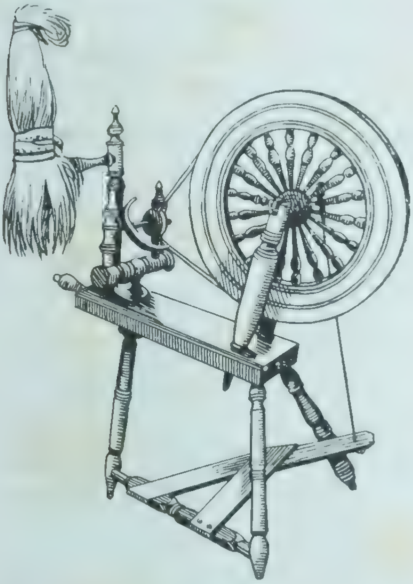

FIGURE 95—*Low Irish spinning-wheel, used for flax.*

II. SPINNING

The prepared fibres of wool, flax, tow, or cotton were spun into yarn either with a spindle-and-whorl or a spinning-wheel. The spindle-and-whorl remained in use throughout the period, particularly for the warp and in the more remote areas, but the spindle-wheel (vol II, p 202) was widely adopted in its diverse local forms.

Known variously as the great wheel, muckle wheel, long wheel, or Jersey wheel, the hand-turned spindle-wheel was still employed, particularly for weft-spinning, until comparatively recent times, and its existence was even further prolonged by its use as a pirn-winder.[1] It still remains the standard wheel of the less advanced communities.

The characteristic wheel of the period was undoubtedly the flyer-wheel, which was invented during the fifteenth century (vol II, p 203). Continuous action and the seated position of the operator allowed a foot-treadle to be incorporated. The invention of the treadle is usually attributed to Master Jürgen, a mason of Brunswick, in 1530 [11], but he was anticipated by an illustration of such a mechanism in the Glockendon Bible of 1524 [12], and it is probable that it was an English conception [13]. The treadle was a simple device pivoted between two of the legs and attached at the far end, by a loop of cord, to a connecting-rod, which fitted round a crank at the end of the axle of the wheel, and thus caused the wheel to rotate when the treadle was depressed. This treadle-wheel could be driven by two cords or a single cord. In the former both the bobbin and the flyer are driven, whereas in the latter only the bobbin is driven, the flyer being dragged round by the yarn. An adjustable friction-band rubbing on the flyer-pulley enabled the tension to be regulated to provide the slip necessary for even twisting as the diameter of the yarn wound on the bobbin increased. A similar result is obtained if the flyer is driven and the bobbin retarded by a friction-band, and normal double-drive wheels were often adapted by the spinsters to single-drive with either bobbin- or flyer-lead.

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[1] A pirn is a wooden bobbin fitting the shuttle of a loom and carrying weft.

In spite of the many advantages of a treadle-drive, it is remarkable how many flyer-wheels, particularly in France, remained hand-turned by a knob attached to a spoke or a cranked axle. This left only one hand free to draw out the fibres for the yarn, a procedure impossible except with the long fibres of flax or hemp.

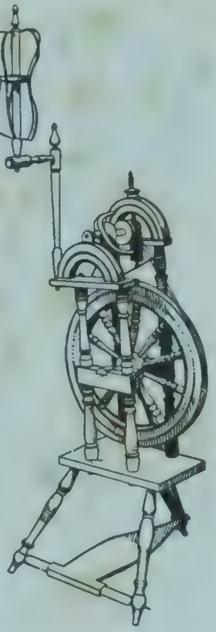

FIGURE 96—*English spinning-wheel, with the flyer mounted above the wheel.*

The treadle-wheel was a product of the Renaissance and as it spread throughout Europe its technical functions were successfully combined with decorative form, so that various types developed, with the flyer mounted beside or above the wheel. The former are known as Dutch or low Irish wheels (figure 95) and the latter as English or Saxony wheels (figure 96). In addition, the Irish castle-wheel was unique in having the flyer mounted below the wheel (figure 97). In North America the spinning-wheel tended to become more utilitarian, and a chair-frame type was produced with a double treadle and an intermediate pulley to increase the speed of the flyer. A flax-spinning wheel with two flyer-and-bobbin units, probably originating in Austria, was introduced into Britain in the eighteenth century.

The distaff became increasingly elaborate. Although usually attached to the spinning-wheel it was frequently mounted on a low stool. A tall distaff is characteristic of flax-spinning; a water-container is often attached for the spinster to wet the fibres as she spins.

Spinning had always been the slowest of the textile processes, and, while the treadle-wheel increased the speed slightly, three to five spinsters were still required to keep one weaver supplied with yarn. The invention of Kay's flying shuttle in 1733 (p 169) increased the disparity, and inventors turned their attention to methods of increasing the rate of yarn-production. Their attempts had been foreshadowed about 1490 by Leonardo da Vinci, who in his *Codice Atlantico* sketched a double flyer to produce two threads simultaneously. He also designed a machine with many such flyer units mounted horizontally, but his ideas were never put into practice. In 1678 Richard Dereham and Richard Haines patented a hand-turned drive to operate 6 to 100 spindles for as many spinsters [14], but it was Lewis Paul of Birmingham, in association with John Wyatt, who attempted the first practical solution to the problem. His patent specification of 1738 [15] describes a system of roller-drafting by means of a series of pairs of rollers, each successive pair revolving faster than its predecessor. He also made provision for one or more of the pairs of rollers to rotate around the axis of the thread to give a slight twist, or for only a single pair of drafting-rollers to be employed. Another patent by Paul in 1758 [16] describes two rollers, on one of which the continuous sliver is wound, feeding a bobbin and flyer revolving proportionately faster so that the sliver is drawn out and spun as it is wound on to the bobbin. His sketch shows about 24 spindles mounted in a circle around a vertical driving-shaft (figure 98).

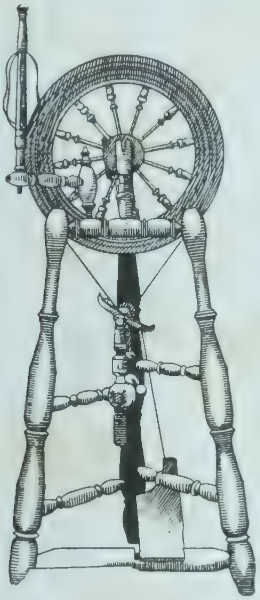
FIGURE 97—*Irish castle-wheel (mainly used in Antrim and Donegal).*

A frequently overlooked patent of 1754 by James Taylor of Lancashire [17] describes 'an engine to be worked either by men, horses, wind or water, for spinning cotton wool into yarn'. No illustration is attached but the machine is described as having a row of vertical spindles on which are fitted bobbins of roving, and these rovings are spun from the points of the spindles to a reel. The reel is provided with a crank-and-ratchet mechanism so that it winds and stops alternately, spinning 2 ft of thread at each operation and then winding it on.

There is no record of Taylor's patent having been put to practical use, but Paul's machine was in use in 1741 at Birmingham, driven by two donkeys, and in 1743 at Northampton, driven by a water-wheel. Since it was not fully successful, its true value lies in the subsequent embodiment of its principles in the first satisfactory spinning-machine.

III. REELING, WARPING, DRESSING

The spun yarn was wound into a hank for washing, bleaching, sizing, or other treatment. The cross-reel (vol II, figure 173) was widely employed for this purpose and the method of reeling produced a hank twice the length of the reel.

The cross- or hand-reel was, however, subject to wide errors in measurement and its use was prohibited in Scotland in 1695, when the check-reel of fixed dimensions was made compulsory. This was a rotary reel with a chain of gears that produced an audible click after a certain number of revolutions. The circumference of these check-reels was closely regulated in many countries: in England woollen and cotton reels were 1½ yds in circumference and in Scotland the flax reel was 2½ yds and the wool reel 2 yds. Hanks varied in length but became standardized in England at woollen hanks of 256 yds; worsted skeins of 560 yds; linen cuts of 300 yds; and cotton hanks of 840 yds.

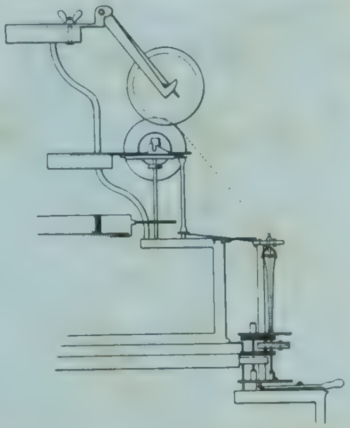

FIGURE 98—*Lewis Paul's spinning-machine, from the patent of 1758. The carded fibres were joined into a long sliver, which was passed between two rollers and compressed, then drawn out by the more rapidly rotating spindle and flyer. A number of pairs of rollers and spindles were mounted in a circle round a central shaft, which drove the lower rollers and the spindles.*

The hanks were washed to remove oil and dirt. Flax and cotton were boiled in soap or potash solution containing a little flour, and woollen yarns were sized with an extract of parchment or rabbit skins.

After treatment the hanks were slipped over adjustable or conical hank-holders and wound on to spools for the warp or quills for the weft. This was often accomplished with a spindle-wheel, but special wheels (both hand-turned and treadle-operated) were in use. An improved hank-holder with two conical cages, known as a 'swift', was introduced in the early eighteenth century.

The warp was still prepared on pegs driven into a wall or on a warping-frame, but during the seventeenth century the warping-mill was introduced and was in use in Scotland in 1687 [18]. This was a large reel (figure 99) about 6 ft high and 3 ft across turned by hand around a vertical axle. Threads from 20 bobbins in a rack were drawn off through a hole-board held in the hand and wound spirally upon the reel. When the required length of warp had been obtained, forming a portee,[1] the threads were passed round a peg at the top and the direction reversed to wind another portee alongside the first. This was repeated, maintaining a cross-over of threads on pegs at each end, until the warp contained the required number of threads. More advanced models of the warping-reel were turned by a handle working a rope and two pulleys, and the hole-board was replaced by a heck-box which was automatically raised by a cord winding round the axle of the reel. The heck-box contained a miniature heddle which served to separate the alternate threads to form the cross-over, and could accommodate forty threads.

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[1] A portee is a convenient group of warp threads: in this instance twenty threads.

The warp, looped up into a chain to prevent entanglement, was inserted in the loom by winding it upon the warp-beam through a wooden comb or raddle to space the threads evenly.

Warps of flax, cotton, or woollen yarn are dressed to strengthen them during the weaving operation and to render the cloth smooth. Woollen yarn was usually dressed before warping, but flax or cotton-warps were dressed in the loom by brushing on a starch-paste made by boiling wheat-flour or potatoes in water. Occasionally a little herring- or beef-brine was added to prevent complete drying of the yarn. The portion of the warp between the heddle and the warp-beam was treated, and when it was sufficiently dry a little grease was brushed in. This dressing was repeated after each section was woven, and linen-looms were often fitted with an arrangement to extend this section of warp for dressing.

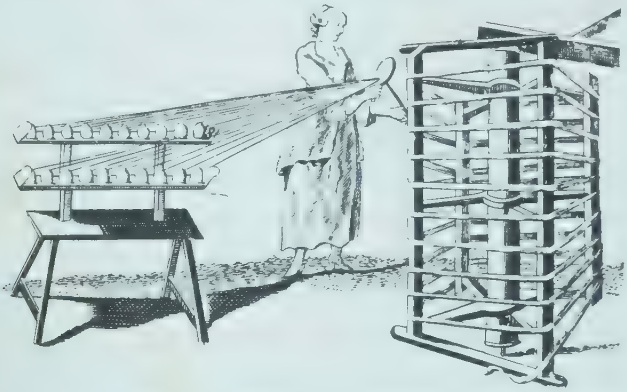

FIGURE 99—*Warping-mill. From an eighteenth-century engraving.*

IV. WEAVING

Plain looms. The various types of loom described in volume II (ch 6) continued to be used throughout the present period, but the horizontal frame-loom, or treadle-loom, supplanted all others in the more advanced countries of Europe and Asia. It became the standard loom for all plain and simple pattern-weaving, and was adapted for various types of fabric.

The Dutch loom was extremely heavy, with a device to facilitate dressing the warp, and was suitable only for heavy linen cloths. The French and English looms were less robust, while the low Estille was designed for fine cambrics. Velvet-looms were specially designed (p 204).

The simple draw-loom. Pattern-weaving was limited by the number of heddles that could conveniently be worked between the reed and the warp-beam. This number did not normally exceed twenty-four, and for the weaving of more intricate patterns the draw-loom was employed.

The origin of the draw-loom is unknown but undoubtedly it first appeared in the east for the weaving of silk. In Europe it was naturally first introduced into the silk-working centres of Italy during the Middle Ages and thence followed the silk industry into France. The sixteenth-century draw-loom was much improved by the inventions of Galantier and Blache in France (1687), and of Joseph Mason in England in the same year [19]. The improved button draw-loom was employed until the end of the eighteenth century.

The essential features of the draw-loom are described elsewhere (p 187). In the button draw-loom, the simples[1] were united in groups according to the pattern and passed through a second comber-board to terminate in buttons or small weights. When a button was pulled down the appropriate leashes were raised to produce the correct shed for that particular passage of the shuttle (figure 124).

The pattern was produced by pulling the cords in the correct sequence while the weaver threw the shuttle through the resultant sheds. The task of pulling or drawing the cords was performed by the 'draw-boy', who was usually an unskilled assistant working from a squared and coloured chart (figure 128).

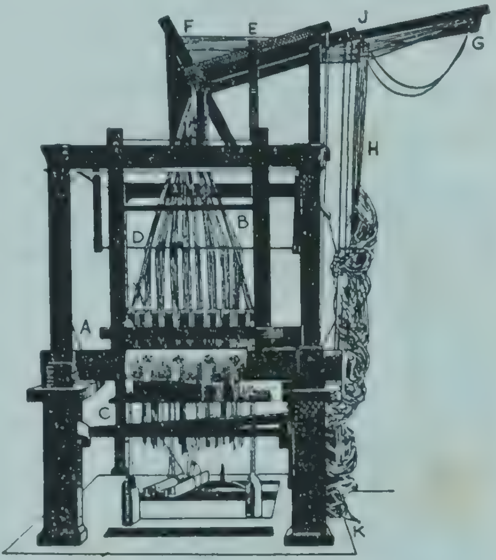

FIGURE 100—*Loom invented by the Lyons weaver Claude Dangon,* c *1605–20, showing his improvement of the figure-harness.* A, *warp-threads;* B, *couplings;* C, *lingoes;* D, *comber-board;* E, *tail-cords;* F, *pulleys;* G, *rod to which ends of tail-cords are knotted;* H, *simples knotted to tail-cords at* J *and anchored at the base* K. *The leashes are knotted to the simples and each set of leashes to be drawn together is knotted to a single* gavacine. *The pattern was made by drawing the appropriate* gavacines *before each throw of the shuttle, hence raising the required warp-threads. For further explanation see p 189 and figure 124.*

The button draw-loom was limited in its application by the weight of the large number of lingoes which had to be raised by the draw-boy, until about 1600, when Claude Dangon invented a loom (figure 100) that permitted an increase in the number of leashes from 800 to 2400. The simples extended to the floor and a lever sliding behind the selected cords enabled the draw-boy to lift the additional weight of the lingoes (p 189). This loom, as the lever draw-loom, continued in use for weaving damask until after 1800.

The automatic draw-loom. The inconvenience of employing an assistant, together with the errors it entailed, led to a search for a mechanism that would automatically perform the work of the draw-boy, and at the same time facilitate changes of pattern. It took a skilled person about a fortnight to set up the leashes and cords of the simple draw-loom for a particular pattern, work which had to be repeated whenever a major change of pattern was desired.

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[1] Apparatus for raising the warp-threads.

As France was the land of figured weaves it is not surprising that most developments in shedding-mechanisms originated there. The first notable achievement was that of Basile Bouchon who in 1725 designed a mechanism selecting automatically the cords to be drawn (figure 101). The cords of the simple passed through eyes in a row of needles sliding in a box. Selection was effected by a roll of paper perforated according to the pattern and passing round a perforated cylinder. When this cylinder was pushed towards the box the needles meeting unperforated paper slid along, carrying their cords with them, while the others passed through the holes and remained stationary. The selected cords were drawn down by a foot-operated comb acting on beads attached to them. Before each shuttle-throw the cylinder was rotated to present the next series of perforations, and the appropriate cords were drawn down.

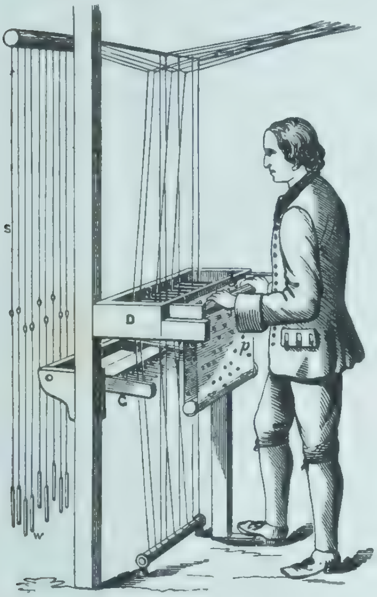

FIGURE 101—*Bouchon's mechanism for selecting the cords, 1725.* (S) *Leashes;* (W) *lingoes;* (D) *needle-box;* (b) *cylinder;* (p) *perforated paper;* (G) *comb-bar acting on knots or beads on vertical simples.*

Three years later Falcon improved the mechanism by increasing the number of needles to several rows and by substituting a series of rectangular cards for the roll of paper. These perforated cards were strung together to form an endless series, and the selection was obtained by pressing the appropriate card against the needles with a perforated platten held in the hand.

Looms incorporating these devices were not successful, although they facilitated change of design, eliminated errors, and could be operated by a single weaver. Adaptations of the same principles were, however, successfully applied to multi-heddle looms, where the problems were simpler because the number of cords to be operated was less.

In 1745 Jacques de Vaucanson (1709–82), an inventor famous for mechanical marvels, constructed a loom (cf. plate 8 A) that improved on the ideas of Bouchon and Falcon. He eliminated the simple and the tail-cords and mounted his selecting-box above the loom so that it acted directly on hooks attached to the neck-cords. These hooks passed through needles and were raised as required by a strong metal bar. The needles were selected by perforated cards passing round a complicated sliding cylinder, and the selection was effected without the aid of a draw-boy.

There is no evidence that this mechanism was adopted, for it was unworkable and suffered the disadvantage of a very complex cylinder. It was only rescued from oblivion by an accident, in that it served as the foundation for the successful Jacquard loom.

Power-looms. While improvements in the shedding-mechanism were being sought in France, other inventors were engaged on the design of a loom that would weave automatically. Leonardo da Vinci forestalled them all by working out, about 1490, certain primary principles of such operation [20]. His sketches are neither clear nor to scale, but it is evident that his shuttle was to be carried half-way through the shed by an arm operating from one side of the loom and its travel completed by a similar arm working from the other side. The mechanism was incomplete and the loom remained purely hypothetical.

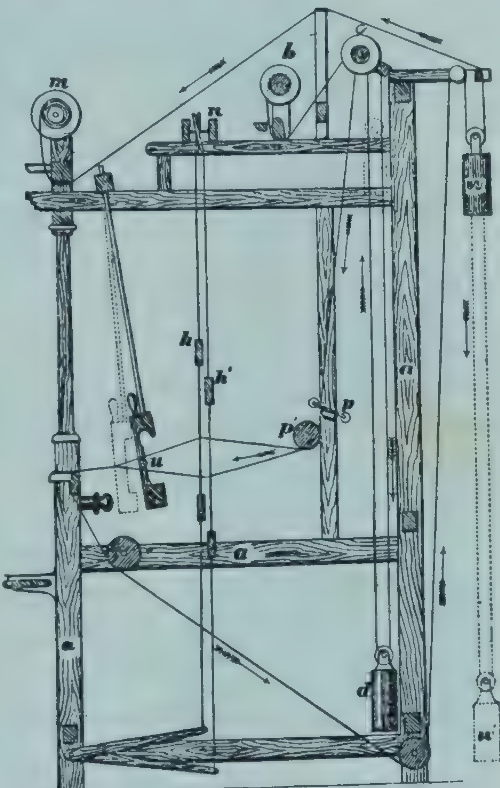

FIGURE 102—*Dutch ribbon-loom.* (b) *Warp-reel;* (c) *pulleys;* (d, w) *weights;* (p) *beam;* (h, h′) *heddles;* (u) *reed;* (m) *cloth roller. The warp passes in the direction of the arrows.*

Anton Möller of Danzig is said to have invented about 1586 a loom that could be operated by an unskilled person who merely supplied power by working a bar or lever [21]. That such looms did exist is shown by the disturbances provoked by their use in Leiden in 1620, and by Dutch ordinances of 1623 and later regulating their use. Many cities issued edicts against them in the early seventeenth century; the looms and their products were prohibited in Germany from 1685 to 1726. An automatic loom of some kind was introduced into London in 1616 and was the cause of riots in 1675 [22]. Known as the bar-loom or Dutch loom-engine, this was a ribbon-loom capable of weaving four to six ribbons simultaneously. The number of ribbons was increased to 12 by William Dircxz in 1604, to 24 by 1621, and eventually to as many as 50. Until after 1800 it could be used only for plain weaves.

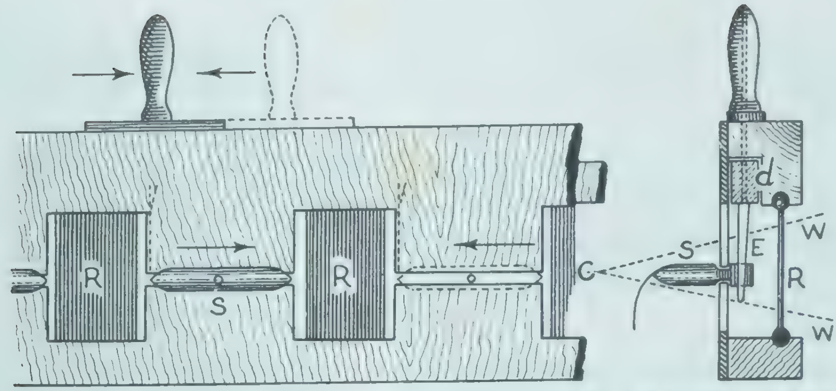

FIGURE 103—*Shuttle-mechanism and batten of the swivel-loom, profile and section.* (R) *Reed;* (W) *warp;* (C) *cloth;* (S, S) *shuttles sliding in openings between planks;* (d) *shuttle-driver;* (E) *pegs by which the driver impels the shuttles through the warp.*

The swivel-loom or new Dutch loom was an adaptation of the Dutch loom-engine and could weave 24 laces at once (figure 102). Each shuttle ran in a slot in the batten between the spaces for the individual reeds, and was driven through the shed by a short arm attached to a handle. The shuttles were all driven simultaneously and each took the place of its neighbour to the right or left alternately (figure 103).

In 1745 John Kay and Joseph Stell patented a method of controlling the pedals by tappets [23], and about the same time the rack-and-pinion shuttle was introduced, with a rack on the upper side of each shuttle that engaged a pinion between each shed (figure 104).

About 1730 Hans Hummel of Basel devised a method of operating ribbon-looms by water-power, but was prohibited from using it. In 1760 a factory at Manchester installed water-driven swivel-looms, but failed owing to the unreliability of the invention and the necessity of having a supervisor to each machine. The dream of an automatic power-loom was thus almost realized with respect to ribbon-looms having a warp only a few inches wide, but the problem of dealing with a wide cloth remained.

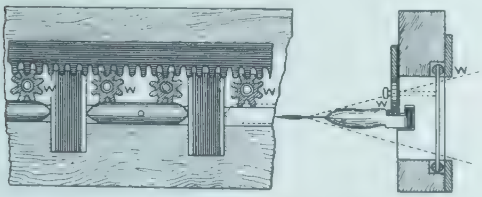

FIGURE 104—*Rack-and-pinion shuttle. Small racks on the shuttles engage with the pinions* W. *Movement of the large rack propels all shuttles through the sheds.*

In 1678 M. de Gennes, a French naval officer, described a loom 'to make Linen-cloth without the aid of an Artificer'. An overhead shaft bore cranks raising the heddles and quadrants operating the spring-loaded beater (figure 105). The weft was inserted by arms that shot in and out of the warp from opposite sides and transferred the shuttle. It was claimed that one water-wheel could drive ten to twelve such looms and that any width of cloth could be woven, but there is no record of such a loom being used.

The next step was one of the simplest yet one of the most decisive in the search for an automatic loom. This was the flying shuttle patented by John Kay of Bury in 1733 [4]. He had previously, in 1730, patented a machine for twisting worsted yarns or thread [24], but his shuttle-mechanism made him famous. A leather driver or picker slid along a metal rod at each end of the batten, and a loose cord with a wooden handle in the centre joined the two pickers. When the cord was jerked in one direction the picker shot the shuttle through the warp (figure 106). The shuttle was stopped by the opposing picker, and a jerk in the opposite direction shot it back. The shuttle was provided with four wheels and was guided by a shuttle-race attached like a ledge to the batten beneath the lower warp-threads. By this means cloths of any width could be woven by one person, and the rate of weaving was considerably increased. The true value of Kay's invention, however, lay in its subsequent adaptation to automatic weaving.

Vaucanson's improved loom of 1750 (plate 8 A) was also an attempt to produce a broad power-loom with a friction-driven winding-roller. He was apparently unaware of Kay's flying shuttle and adapted the de Gennes shuttle-arms. The fully automatic power-loom remained little more than an aspiration in 1760, and the practical problems were not solved until the following era.

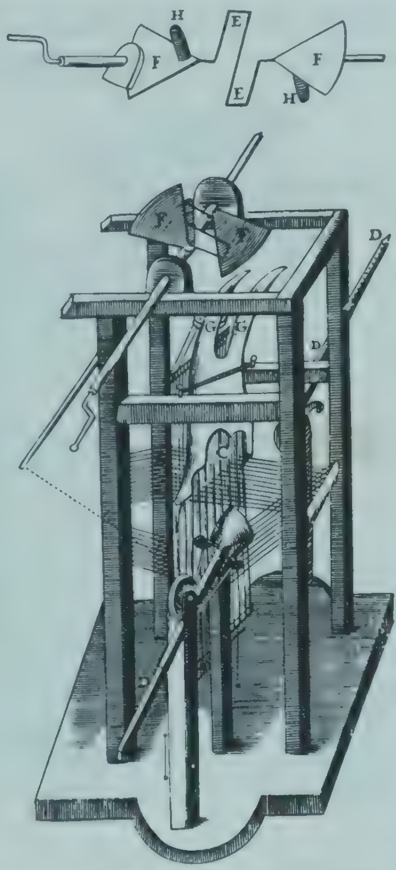

FIGURE 105—*M. de Gennes's 'New Engin to make Linen-cloth without the help of an Artificer'.* (E, E) *Cranks raising the heddles to form the sheds by means of cords;* (F, F) *quadrants acting on levers* G, G, *working the beater* C; (H, H) *cams operating the shuttle-mechanism;* (D, D) *arms transferring the shuttle, meeting at the centre of the shed.*

V. FINISHING-PROCESSES

Scouring and fulling. The woven cloth was first washed to remove any oil or dressing. Linen and cotton cloths were soaked in clear water and washed with soap or potash. Soap was similarly used for woollen cloths, but fuller's earth or pig's dung and stale urine continued to be widely employed for reasons of economy.

After repairing weaving-faults woollen cloth was fulled to thicken it and give it a firm structure. This was done in primitive communities until recent times by tramping or 'waulking' the cloth with the feet (cf vol II, figure 186). In more advanced cloth-working centres, however, the fabric was generally fulled in fulling-stocks, first illustrated in Italy in 1607 (vol II, figure 187), but already widely employed in the late Middle Ages. Similar stocks are illustrated in Germany in 1735 [25], and in France in 1733 [2], driven by water-wheels, while Dutch illustrations of 1734 [26, 27] depict stocks driven by windmills. Horse-gins were also used to furnish motive-power, and occasionally the stocks were hand-driven.

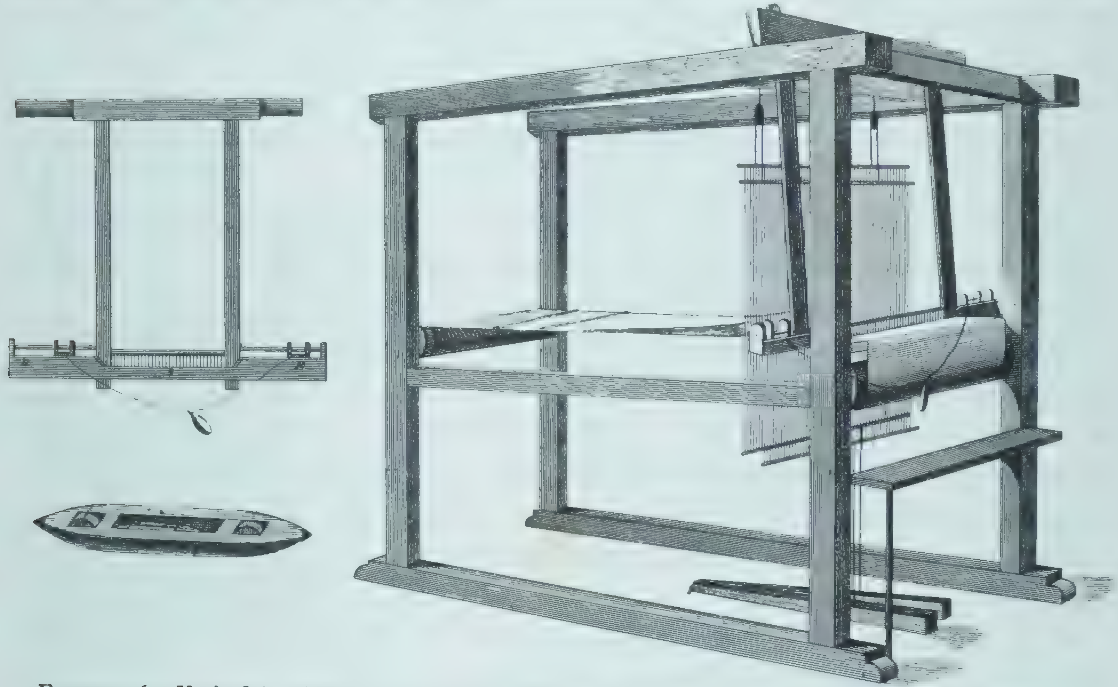

FIGURE 106—*Kay's flying shuttle, 1733.* (Right) *The complete loom;* (left) *the batten on which the shuttle travels, with the operating-cord; and* (below) *the shuttle.*

These early eighteenth-century fulling-stocks were of two types: hanging-stocks with the feet or hammers pivoted at their ends, and falling-stocks with the feet dropping vertically between guides. In both types the feet were raised by tappets on a horizontal driving-shaft and allowed to fall on the cloth bundled in the trough or stock below. The heavy oaken feet were stepped and the stocks so shaped that each time the cloth was pounded it rotated a little to ensure uniform action and prevent damage. In fulling caps and stockings the feet were often equipped with wooden pegs or with horse's or bullock's teeth.

The cloth was treated with hot soapy water with fuller's earth added—soap alone was too expensive. The finest soap was obtained from Castile and Genoa.

In France in 1751, 10 lb of soap was the recommended weight for fulling a piece of white cloth 45 ells long, and 15 lb for coloured cloth. Half the soap was dissolved in two pails of water as hot as the hand could bear, and the solution was poured over the cloth as it was laid in the stock. After 2 hours' fulling the cloth was taken out and smoothed, and immediately returned for a further 2 hours' treatment. It was then wrung out, the remainder of the soap similarly dissolved was added, and the fulling was continued until completed, the cloth being taken out and smoothed every 2 hours. Finally the cloth was scoured in the same stock in hot water and rinsed in running cold water. In 1669 French fullers had to use 4 pints of fine oatmeal vat-gruel in every fulling-trough, and not more than two pieces of fustian or four camlets were to be treated at one time. English regulations insisted that not more than one broadcloth or two half-cloths were to be placed in the stocks at the same time [28]. Occasionally cloths were fulled a second time after the first raising.

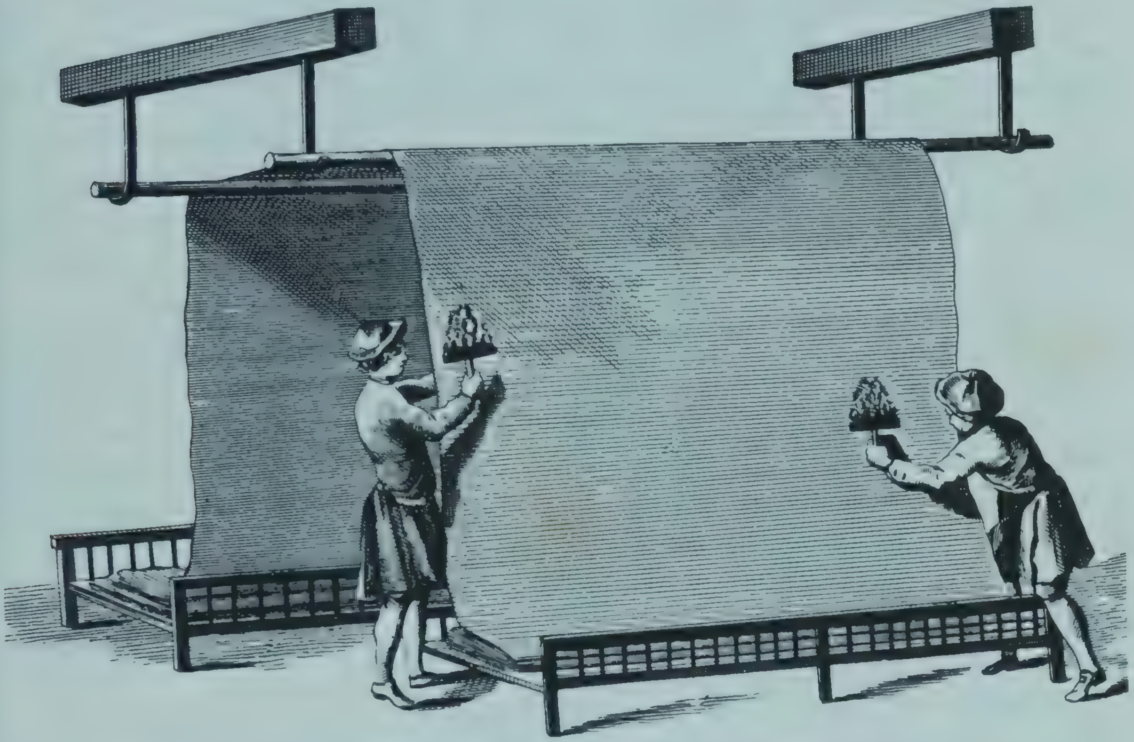

FIGURE 107—*Raising the nap on cloth with mounted teazels, c 1760.*

Stocks were also used for the preliminary scouring process, but scouring-stocks had lighter feet and were so poised that they acted almost horizontally, in order to lessen the pounding. Fuller's earth, from which grit and stones had been carefully removed, was used with a copious supply of cold water. Black soap was also employed, and the final rinsing was carried out on the banks of a stream or from tethered rafts floating in a river, the cloth being manipulated with long poles.

After fulling or scouring the cloth was dried on tenter-frames. These consisted of upright wooden posts with a fixed upper rail and a lower rail whose position was adjustable by pegs or wedges (vol II, figure 184). Both rails were fitted every two or three inches with tenter-hooks—L-shaped double-pointed nails—those in the top rail pointing upwards and those in the bottom rail downwards. The wet cloth was hooked by its lists (selvedges) to both rails and the lower rail adjusted to draw the cloth tight and of even width. Over-stretching on the tenters was a common abuse and consequently their use was at times prohibited; in most European countries the stretch was limited to between 5 and 10 per cent of the length and breadth.

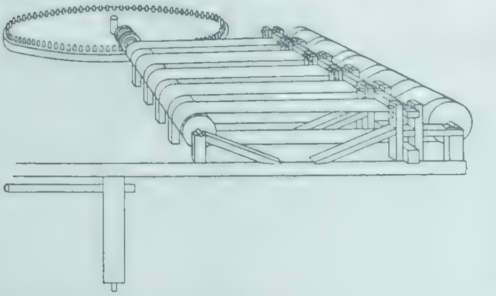

FIGURE 108—*Leonardo's gig-mill. From the* Codice Atlantico.

Raising, cropping, and frizing. The raising of the surface of woollen cloths by hand, by means of wooden or metal implements containing teazel-heads (figure 110, and vol II, figure 189), continued until the nineteenth century. The cloth, sprinkled with water, was hung over a pole or laid on a bench while its surface was rubbed with the teazels (figure 107). The first gentle raising-strokes were followed by a brisker action, and always the cloth was raised first against the pile and then in the direction of the pile. It was dried before being cropped.

Machines for raising cloth were introduced in the fifteenth century if not earlier. Though the use of such 'gig-mills' was prohibited in England by an act of 1551, they were in use at Gloucester before 1640. The earliest illustrations of gig-mills are found in two sketches by Leonardo da Vinci of about 1490 [29]. The first shows a hand-driven device, but the sketch is not readily understood. The second shows a multiple machine to be worked by a horse turning a winch (figure 108). The cloth with its ends sewn together passed round two rollers, one of which was driven, and as it travelled it passed beneath an adjustable beam, the under side of which was covered with teazel-heads. Five cloths could be raised simultaneously.

This proposal for raising with fixed teazels was unusual. In the raising-machines employed throughout this period (and indeed up to the present day) a teazel-covered roller rotates while the cloth passes under it in the opposite direction. This principle was first illustrated by Zonca in 1607 (figure 109).

Coarse woollen cloths were often raised with flatter-cards, which were merely enlarged hand-cards with wire teeth; their use was prohibited in England in 1511 and in France in 1669.

The cropping of woollen cloths after the nap had been raised still furnished work for the shearman. The stirrup-grip, with the hand acting as a lever (figure 110), was employed to the end of the seventeenth century, but during the following century an improved device was introduced. This was a lever that rotated around the rear edge of the upper blade and was connected by a double cord to a block attached to the lower blade (figure 111). When the lever was depressed with the left hand the blades closed, and the spring of the bow-stem reopened them. The lower blade was later curved to fit the padded bench, and the

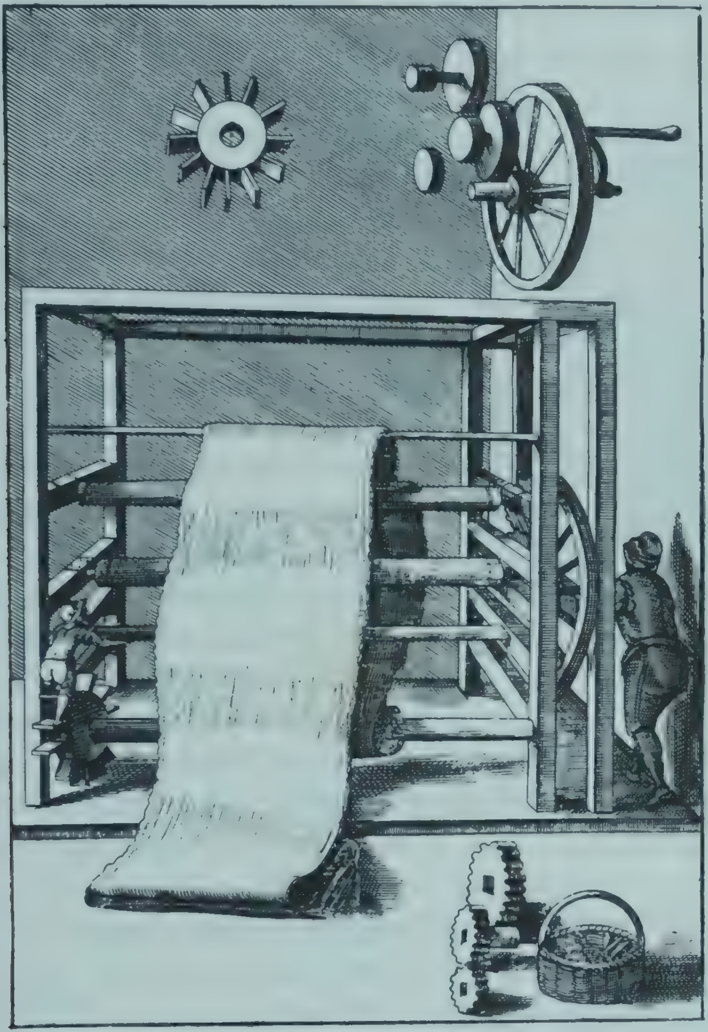

FIGURE 109—*Gig-mill for raising the nap on cloth, 1607.*

upper blade was tilted to an angle that increased to 30° before 1760. Two shearmen usually worked together, and for close cropping leaden weights were laid on the lower blade to press it deeper into the cloth. Cropping followed each raising operation, and in 1748 woollen cloth in France was cropped four or five times on the face and once on the reverse [2].

Cropping was a slow and laborious operation and early attempts were made to mechanize it. The cropping-machines prohibited in England in 1495 may have resembled that sketched by Leonardo (figure 112). This involved little more than a crank-system to open and close the normal hand-shears while automatically progressing over the cloth. Further sketches suggest novel means of using separate blades. Leonardo's designs were abortive and the solution was not found until the end of the eighteenth century.

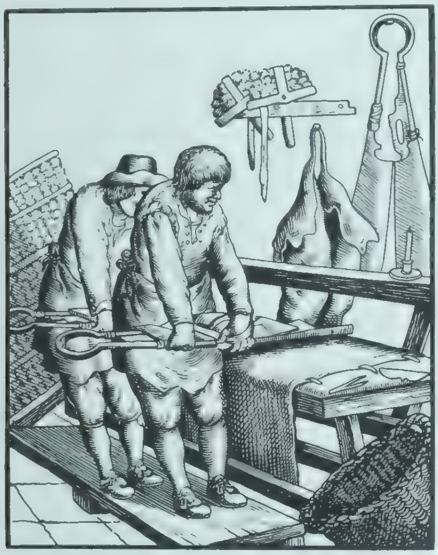

FIGURE 110—*Shearmen at work. From a seventeenth-century engraving.*

During the seventeenth and eighteenth centuries the surface of woollen cloth was frequently frized to give a fashionable appearance. This meant rubbing the nap with a circular motion, giving a granular effect; frizing was originally performed by hand by two workmen working a 2 ft by 1 ft plank over the surface of the cloth, which was previously moistened with egg-white or honey [30]. More generally a frizing-mill was employed, driven by water-, horse-, or man-power (figure 113).

The cloth passed between two planks, about 10 ft long and 15 in wide, being slowly drawn along by a spiked roller. The lower plank was covered with a rough woollen cloth and the upper coated on its underside with a cement of glue, gum arabic, and yellow sand with a little *aqua vitae* or urine [30]. By means of a crank at each end the upper plank was given a very small rotary motion which rubbed the long nap into a uniform series of small hard burrs. Black cloths were usually frized only on the reverse, but coloured and mixed cloths were treated on the face.

Bleaching. Linen and hempen cloths from the loom had to be bleached to make them attractive in appearance and texture. In the early eighteenth century the Dutch were esteemed as the best bleachers in Europe; their method was to 'buck' the cloth by steeping it in hot waste lye, followed by fresh lye, for 8 days.

It was then washed with black soap and wrung dry. The cloth was next steeped in a vat of buttermilk, the lengths being treaded in as the milk was added, where it was allowed to remain under pressure for from one to three weeks. It was again washed with soap, wrung, and spread on the grass for two or three weeks to bleach in the sun. During this period it was regularly wetted. The operations of bucking, souring in buttermilk, and grassing or crofting were repeated five or six times, the strength of the lye decreasing each time. The whole process occupied half a year and could be carried out only in the summer.

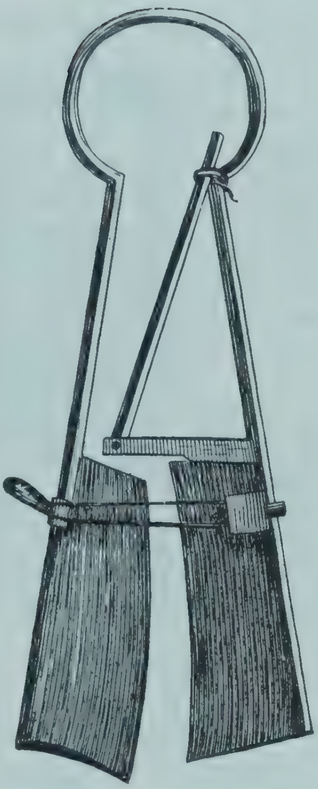

FIGURE 111—*Cropping-shears, c 1760.*

In 1755 at Haarlem, the centre for the manufacture of the whitest and most lustrous Dutch linen, the cloth was bucked for 10 hours in a lye of various ashes and then wetted on the grass for 24 hours [31]. This procedure was repeated ten or more times before the cloth was soured in buttermilk for five or six days. Rye-meal or bran was sometimes used instead of milk. The sequence of souring, washing, bucking, and watering was repeated as often as necessary for from six to eight months before the fabric was starched and dried.

In Picardy at the same date linen was bucked alternately in cold used lye of wood-ashes and hot fresh lye. After each treatment the cloths were washed and exposed on the fields, being wetted from the river with scoops. When sufficiently white they were soaked in sour skimmed milk and dipped in weak starch and smalt or Dutch *lapsi*. After drying on poles they were finally beaten with smooth mallets on marble blocks.

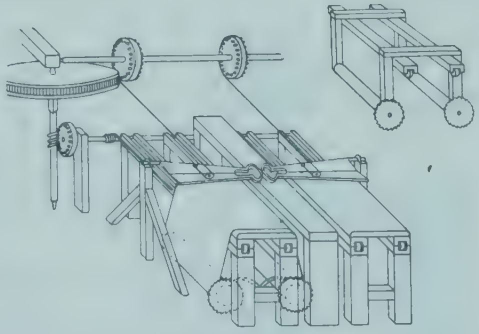

FIGURE 112—*Leonardo's shearing-machine. From the* Codice Atlantico. *The table* (upper right) *is drawn along the main frame of the machine by a cord winding round the lower rotating shaft. The shears have one blade fixed: the second is actuated by another cord, taken to a lever worked by the toothed wheel on the upper shaft.*

In Ireland the cloths were washed and boiled in lye for two hours, which was quicker than steeping. This treatment was repeated six or seven times with exposure and watering on the fields between each. The cloths were then soured in warm water and bran or wheat for three days, washed with soap, and rubbed between boards. Finally the linen was well milled in the stocks, starched, dried, and calendered or beetled. In Scotland the use of lime for bleaching was consistently and unaccountably prohibited from 1648 until after 1815, although the slaked lime used by offenders had no deleterious effect on the linen. Richard Holden of Ireland introduced a cheap method of bleaching with kelp, which was successfully employed near Dundee in 1732. In 1756 the duration of the bleaching process was almost halved by the use of dilute sulphuric acid, instead of the lactic acid of buttermilk, for the souring process. This process was introduced by Francis Home of Edinburgh.

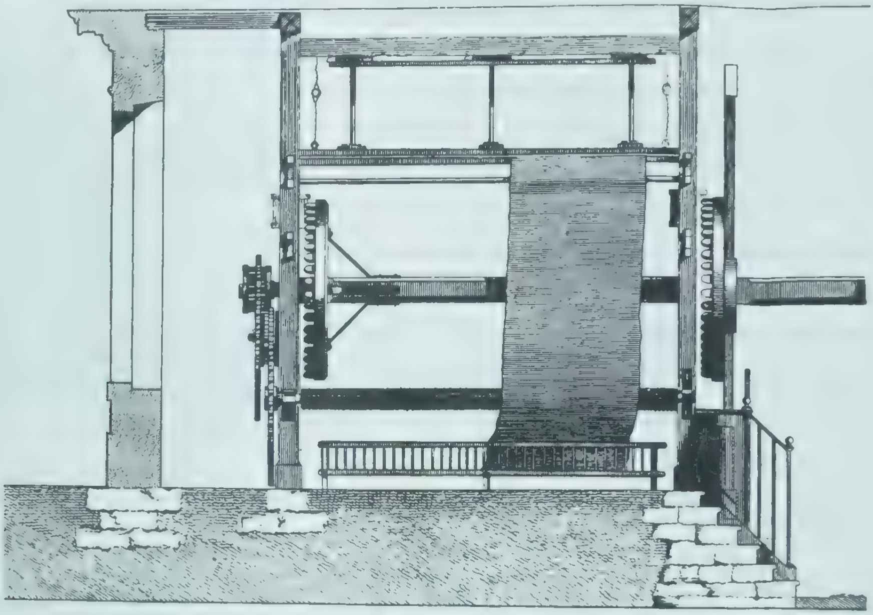

Figure 113—*Frizing-mill, 1763. The spiked roller driven through gears is at the bottom: the vertical pinions rotate the upper plank.*

Hemp was bleached in a similar manner, but as it was a coarse cloth it did not receive such careful attention. Cotton fabrics were bleached in a briefer treatment, the fibres losing their colour more readily than flax does. Wool was bleached after fulling by exposing the half-dry cloth to the fumes of burning sulphur in a closed chamber. Chalk and indigo were often added to the final rinsing-water before the treatment with sulphur.

Pressing. Linen and cotton fabrics were smoothed by rubbing with polished stones or wood before being pressed. Woollen cloths were brushed in the direction of the nap and all loose particles were removed by gentle treatment with a board coated on its underside with a putty made of mastic, resin, powdered stone, and sifted filings. Ironing was also employed, using a large metal box containing the iron-heater. The box was lowered upon the cloth by a rope and pulley and worked backwards and forwards by two men holding long pivoted handles.

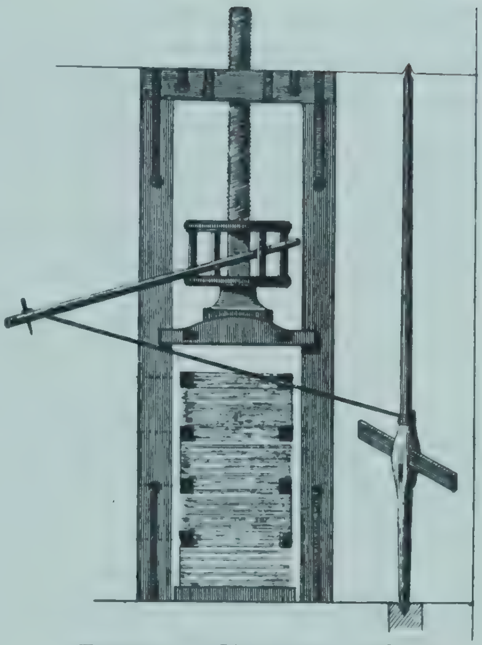
Figure 114—*Linen-press, c 1760.*

In certain parts of France woollen cloths were steamed by supporting them, tightly wrapped on rollers, over boiling water in a square kettle or copper. Elsewhere the cloth was sprinkled on the reverse with gum arabic solution and passed over a burning charcoal fire from one tightly wound roller to another, or between a series of polished iron rods to a single roller.

Most cloths were finally pressed to remove all creases and to impart a gloss. Large screw-presses were turned by levers working in a lantern attached to the threaded column (figure 114). The cloths were carefully cuttled (that is, arranged in suitable folds) and placed between the lower and upper plates with pasteboard, vellum, or wood interleavings. For a greater gloss hot pressing was preferred. The cloth was sprinkled on the reverse with water or dilute gum arabic solution, folded, and interleaved as before, and a very hot brass or iron plate was inserted between every six or seven folds. The cloths were left in the press for from 10 to 12 hours and the process was repeated four or five times with the folds falling in different positions. To obtain great pressure the lever of the press was connected by rope to a winch turned by hand or horse-power.

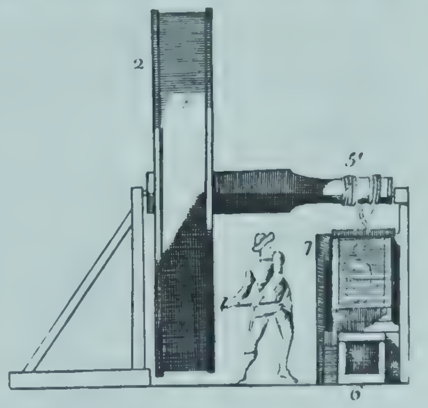

Figure 115—*A calender* (end view); (2) *wheel trodden by two men inside it;* (5) *shaft and ropes;* (6) *table;* (7) *box-weight. From an early eighteenth-century engraving.*

Calendering was frequently substituted for pressing, or used after pressing to impart extra gloss. The calender was a large wooden box filled with stones cemented together and weighing 10 tons or more, which could roll over two very smooth rollers on a flat table (figure 115). The linen or wool cloth was carefully wound round these rollers and the box moved backwards and forwards by means of ropes winding on a shaft turned by a horse-gin or tread-mill. To replace a roller the box was wound to one end and slightly tilted on the other roller. Watered effects were obtained on coarse plain woven worsted or silk cloths by the great pressure of one layer of cloth on another. A remarkable calender built in Paris to the order of Colbert had a bed of polished marble, and the underside of the box was covered with a single sheet of highly polished copper.

APPENDIX

Types of cloth. The various animal and vegetable fibres were used separately or in combination to give a great variety of fabrics. Wool gave the greatest scope and was divided into three fundamental types:

1. Cloths (woollen) of carded warp and weft.
2. Tammies (worsted) of combed warp and weft.
3. Serges (mixed) of combed warp and carded weft.

Each of these types was subdivided into numerous varieties according to the spinning, weaving, or finishing techniques employed.

Some of the principal types of cloths are listed below, but the nature of many of them changed with time and imitations assumed false designations.

Barracan	coarse twilled camlet of wool or goat's hair, boiled and mangled to make it waterproof.
Bays	worsted warp and woollen weft, lightly fulled and raised.
Bombazine	silk or linen warp and cotton weft (also a general term for cotton).
Broadcloth	wide cloth of woollen warp and weft, well fulled.
Calamanco	highly glazed woollen cloth, resembling satin in appearance.
Calico	cotton cloth, usually printed, named after Calicut, India.
Camlet	wool or wool/goat's hair mixture, sometimes containing silk threads.
Cambric	very fine linen cloth, named after Cambrai, France.
Cloth	general term for a fabric of woollen warp and weft, the former S-twist and the latter Z-twist, usually fulled.
Cogware	coarse woollen cloth, fulled and raised.
Crepon	light fabric of worsted or silk/worsted mixture with warp more highly twisted than weft.
Diaper	figured linen fabric, named from the medieval Greek *diaspros*, pure white.
Dimity	heavy figured cotton fabric, named from the Greek *dimitos*, of double thread.
Dowlas	coarse linen cloth named after Daoulas, Brittany.

Drugget	figured cloth of silk, silk/cotton mixture, wool or wool/linen/cotton mixture.
Etamine	worsted warp and weft or wool/silk mixture.
Flannel	loosely woven woollen cloth with roughened reverse.
Fustian	linen warp and cotton weft, named after Fostat, the old name for Cairo.
Grogram	coarse silk and wool cloth, after French *gros-grain*.
Kersey	coarse woollen cloth, fulled (carsay).
Linsey-woolsey	coarse fabric of linen warp and worsted weft.
Manchester cotton	originally a coarse woollen cloth, fulled and raised; later fustian.
Mockadoes	pile fabric of goat's hair. (? Italian *mocaiardo*, haircloth.)
Muslin	fine white cotton fabric, named after Mosul, Mesopotamia.
Ratine	closely woven woollen cloth, well fulled and often frized.
Say	cheap fine cloth resembling serge.
Serge	worsted warp and woollen weft, occasionally fulled and usually twill weave.
Shag	pile fabric of goat's hair.
Shalloon	twill woven worsted, named after Châlons-sur-Marne, France.
Stament	coarse worsted fabric.
Stuff	general term for worsted fabrics.
Taffeta	watered fabric of coarse plain-woven silk, from Persian *tāftah*, woven.
Tamis	fine highly glazed wool fabric, from French *tamis*, a sieve.
Tammy	general term for fabric of worsted warp and weft, both with similar twist. Probably also from tamis, sieve.
Velvet	pile fabric of silk or cotton.
Voile	fine worsted fabric of open weave.

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A NOTE ON KNITTING AND KNITTED FABRICS

JAMES NORBURY

THE origin of knitting is completely unknown. Fragments of fabric, a few sandal-socks, and several Coptic caps provide the only evidence we have for its early history. Even the technique applied to producing a fabric built up from a series of loops, instead of on the warp-and-weft basis as in weaving, is obscure.

There are basic differences in structure between woven materials and knitted fabrics. Primitive woven cloths were formed by interlacing warp and weft threads lying at right-angles to each other throughout the fabric (vol I, ch 16). Early woven textiles were made of thick and coarse yarns yielding a fabric bulky in appearance and stiff in texture. This was probably one of the factors that led to the evolution of knitted fabrics, which arose from the purely utilitarian need for a fabric of greater elasticity than cloths woven on primitive looms. The great advantage of the knitted fabric is its readier adaptability to the shape of the human figure.

The first stage in the evolution of knitting was the development of a technique based on netting, to give a finer mesh than could be obtained by use of the shuttle and netting-rod. Evidence of this development is to be found in fragments of early textiles discovered in Egypt and Scandinavia. They are of a meshed fabric, much more elastic than woven material, to which the Nordic term *sprang*[1] has been applied. *Sprang* fabrics probably originated between 1500 and 1000 B.C. They closely resemble knitting, the difference being that the foundation loops out of which *sprang* is built up are interlocked vertically instead of horizontally as in true knitting.

Two techniques appear to have been used in the making of *sprang*. In the first, the fabric was formed with a needle, derived from a netting-needle and in many ways resembling the modern sewing-needle, in the following way:

First the warp was made by arranging a number of closely spaced parallel vertical threads, each as long as the width of the finished material and kept taut by tying their ends to the top and bottom of a large rectangular frame (figure 116). A very simple stitch, consisting of a uniform twist, was worked up the first thread and fastened off at the top. A second row of these twisted stitches was then worked up the second thread, each stitch being interlaced through the side of the stitches twisted on the first warp thread. This action was repeated up every thread of the warp until a meshed fabric had been formed enveloping every thread of the warp. The two ends at the top and bottom of the interlaced threads were fastened off to make them secure; the warp threads were unknotted and withdrawn; and a piece of meshed fabric resembling a very fine piece of netting was obtained.

Once this simple technique of needle-weaving had been mastered, variations in the types of fabric were rapidly evolved. In one of the existing fragments of *sprang* a half-knot technique was employed to keep each loop in place. This gave the fabric a symmetrical foundation, and upon close examination the resultant material has the appearance of a very fine fishing-net.

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[1] Icelandic *sprang* means lace weaving.

Another variant of *sprang* fabric was made by working a chain-stitch up the first warp thread in place of the simple coiled stitch. Chain-stitch was then worked up each of the remaining warp threads, the stitches being interlaced vertically through the side of each chain. The warp threads were withdrawn and a fabric so closely resembling knitting was produced that early fragments of this type of *sprang* were described until recently as the earliest examples of knitted fabric.

In the second technique of making *sprang*, which was more highly developed, instead of using warp threads built on a rectangular frame as a temporary foundation for the fabric, a single continuous warp thread was formed into a plaited mesh on the rectangular frame (figure 117). The work was begun from the centre of the frame. Each time the threads were plaited, two thin sticks were inserted at the top and bottom to hold in place the loops formed by the plaiting action. After the next series of plaits had been made and two more sticks had been inserted, the first two, holding the previous set of plaited loops in position, were withdrawn and could be used again. This action was repeated first from the centre to the top of the frame and then from the centre to the bottom. Thus by working outwards from the centre a piece of fabric was built up having a median axis, on either side of which the stitching was perfectly symmetrical. When the work had been completed the central axis was made secure by knots to prevent the fabric from unravelling when it was taken off the frame (plate 8 B).

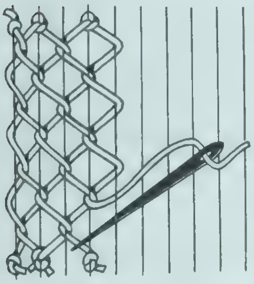


FIGURE 116—*Simple method of making* sprang *by interlacing threads on vertical strands.*

It is interesting that at about the same time as the *sprang* technique was being developed in Egypt, a comparable technique, though on a slightly different principle, was taking shape in Peru. This Peruvian needle-knitting resembled true knitting more closely than did *sprang*. Instead of being worked on warp threads in a frame, a fine woven fabric formed the basis of what is actually a primitive embroidery. The entire surface of the foundation material was covered with a meshed stitch producing a new fabric that could easily be mistaken for a primitive type of knitting. Various colours were used in Peruvian needle-knitting, the resultant fabrics being covered with elaborate patterns not unlike those of Arab colour-knitting.

There is no evidence indicating how the *sprang* and needle-knitting techniques evolved into frame-knitting. There are only sandal-socks from Arabia (figure 118) which may be as old as the seventh century B.C., and a single fragment of Arab colour-knitting found at Fostat (old Cairo) which can be dated between the seventh and ninth centuries A.D. It is worked in crossed stocking-stitch at a tension of 36 stitches to the inch, the patterning being in deep maroon wool on a ground of gold silk. It is one of the finest examples of wool and silk stranded knitting ever found.

In its early stages Arab knitting was worked on frames, and this led gradually to the technique of knitting as practised today. The frames were either circular or rectangular (figures 119, 120) and were fitted with wooden or bone pegs, equally spaced all round the frame. The thinner the pegs and the closer they were together, the finer was the fabric.

Casting on stitches for frame-knitting was very simple. The yarn was tied to the first peg and then wound round each peg in a counter-clockwise direction continuously until every peg on the frame had a crossed loop lying at its base. A second series of twisted loops was then similarly wound round the pegs, the first set at the base of the peg being drawn over the second set of loops that had just been made. Probably this action was originally performed with small sticks, or in coarser fabrics with the fingers. Later a hooked implement was developed to facilitate raising the loops one over the other. When the first set of loops had been drawn over the second, the stitches were cast on and the frame was ready for the knitting to be carried out. This was a repetition of the process of casting-on, the series of loops at the base of the frame being passed over the second set of loops continuously, thus producing a knitted fabric in crossed stocking-stitch. The hooked action led much later to the development of crocheted fabric, probably about the end of the sixteenth century.

Several early investigators of knitted fabrics wrongly assumed that certain woollen caps of Egyptian or north African origin dating from the first century A.D. were crocheted. The fact is that these caps were produced on frames, an early Christian sect having learnt the craft of frame-knitting from the nomads who lived in the Egyptian desert. The rigid frame and hook methods for producing knitted fabrics were to play an important part in the development of knitting on needles as now practised.

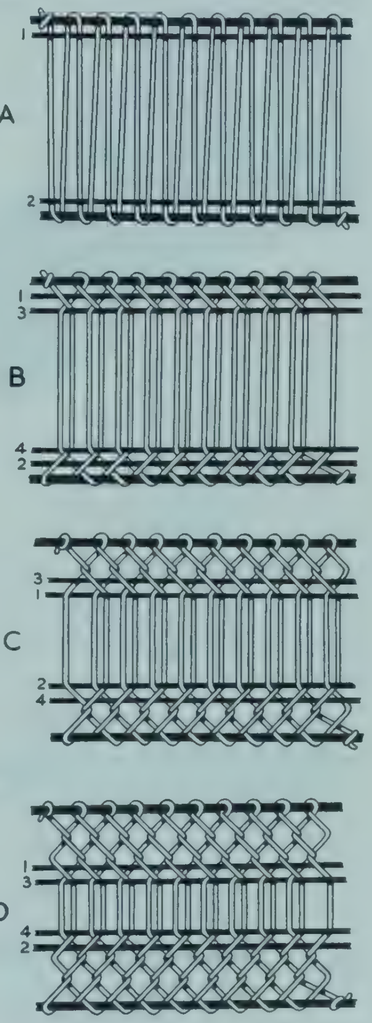


FIGURE 117—*Plaited sprang.* (A) *The first two rods are inserted in the loops;* (B) *two more rods form the first series of loops;* (C) *the first two rods are removed and reinserted nearer the centre, forming more loops;* (D) *the loops are continued towards the centre.*

In all good knitting-techniques one needle is held completely rigid, the other being used for transferring the stitches from one needle to the other while making the fabric. The earliest knitting-needles were hooked, and this type of needle is still used by the shepherds of the Landes district in France. Once the frame-knitting technique has been completely mastered it is a simple matter to understand how the idea emerged of casting the basic loops for the fabric on to a single needle instead of on a series of pegs built into a frame.

One point of great interest is that as late as the beginning of the present century many

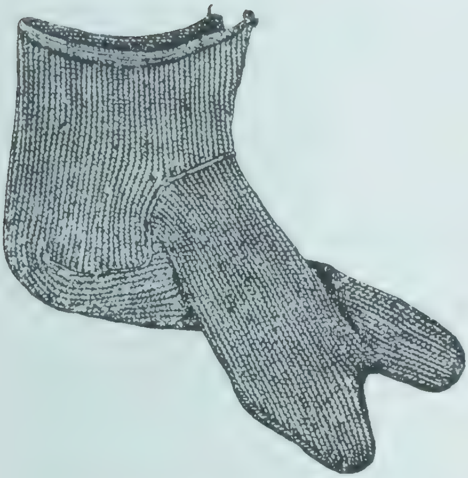
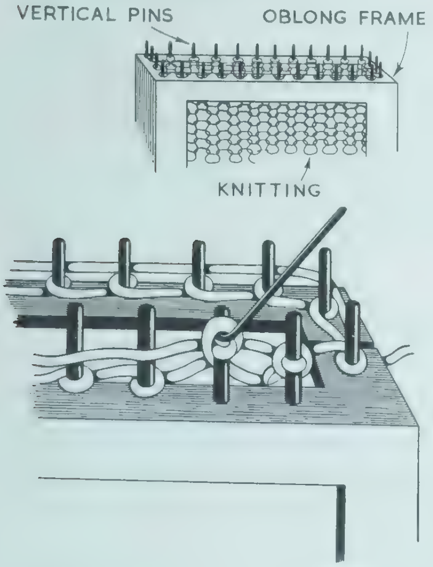


FIGURE 118—*Arab sandal-sock of red wool.*

knitters in rural districts in all parts of Europe used a similar method for casting stitches on needles as that used in primitive frame-knitting. Twisted loops were passed from the thumb on to the needle. When the required number of loops had been made, the wool was wound over the point of the needle in front of the first loop, the loop then being drawn over the wool with the second needle. This action was repeated until all the loops had been worked off, when the cast-on was completed and the worker was ready to begin knitting.

The series of rigid pegs was thus replaced by a single needle, held firm by pushing one end into a knitting-stick or knitting-sheath (figure 121). Early knitting-sticks were simply square or circular pieces of wood with a hole drilled in one end. With the needle inserted in the hole, the stick was tucked into a belt worn round the waist. The stitches were then cast on to this fixed needle by the method described in the preceding paragraph. Knitting-sheaths developed from knitting-sticks, many of which were carved with very elaborate patterns, some of them being masterpieces of craftsmanship.

Another type of knitting-sheath common among agricultural workers and fishermen was made from a series of quills bound together, the needle being pushed into the open end of a quill. Knitting-pouches consisted of a pad made of fabric or leather mounted on a belt. These pouches were stuffed with straw, wood-shavings, dried grasses, or horsehair, the end of the knitting-needle being stuck through the fabric into the stuffing and thus held firmly.



It is worth noting incidentally that changes in fashion influenced the evolution of the knitting-sheath. In Yorkshire, for instance, where knitters continued their work while walking the lanes and doing their business with shopkeepers, the sheath was made with a flat, curved end that could be tucked under the arm just as easily as pushed into the belt, and out of this new method of under-arm knitting the technique of holding the right-hand needle under the arm came into being. This method is universally used today in all countries where the knitting tradition has persisted.

The south of England is an exception to this principle since here a short needle is used, not long enough to tuck under the arm. This exception is accounted for by the virtual disappearance, from the end of the reign of Elizabeth I to mid-Victorian times, of hand-knitting from southern England.

The development of *lace fabrics*, from the simple stocking-stitch of the early knitters, is one of the most fascinating stories in the history of textile development. These fabrics are built up from a series of eyelets, formed by working made loops and decreases on a stocking-stitch foundation. *Cable fabrics*, probably originating with fishermen in imitation of the twist of ropes, are made by passing one group of stitches behind or in front of a second group of stitches. *Coloured knitted fabric* is a patterned fabric in stocking-stitch with two or more colours in each row. The stitches are knitted in the ordinary way, the colour not in use being either stranded across the back of the fabric—the stranding principle was used in all early knitted fabrics—or woven round the strand of fibre that is being used to knit the stitches. Colour-knitting was developed first in the Near East, and appeared later in all parts of Europe. Spain appears to have been first in the European field with this type of fabric, and a very fine example of this type of knitting is seen in a Spanish altar-glove of the eleventh century (plate 9 A).

Florentine knitters of the sixteenth and seventeenth centuries perfected the art of making coloured and brocaded fabrics. Their magnificent knitted and brocaded coats were worn by courtiers in all parts of Europe (plate 9 B).

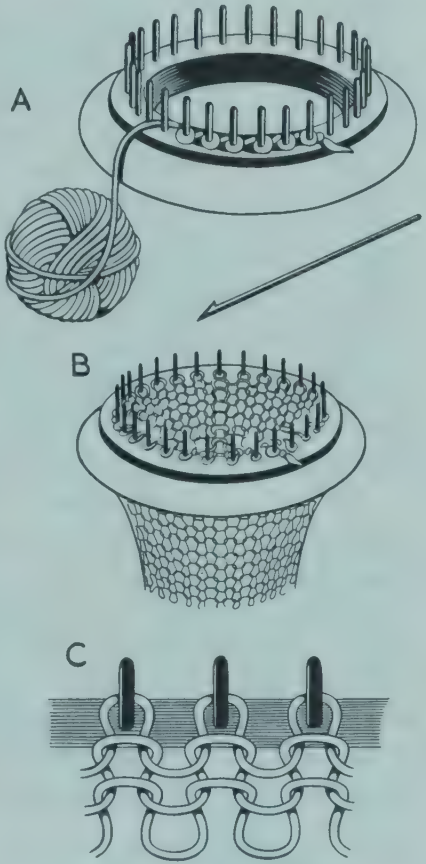


FIGURE 120—*Knitting on a circular frame.* (A) *Casting on;* (B) *formation of the fabric;* (C) *detail of the loops.*

During the reign of Elizabeth I, William Lee (d *c* 1610), a clergyman and a Cambridge graduate, devised the first frame-knitting machine. This employed a combination of Arab frame-knitting and the hooked knitting-needle technique already described. Lee's very ingenious machine had a series of rigid hooks, with a second series of moving hooks at right-angles to them. The stitches were cast on the series of rigid hooks in exactly the same manner as with an Arab knitting-frame. The movable hooks, manipulated by a simple mechanical action, were now inserted into the stitches on the series of rigid hooks. The yarn was then laid horizontally under the rigid hooks, and the stitches were drawn over it by the movable hooks. This simple action is basic to all types of knitting-machines, and Lee's invention led to the establishment of the machine-knitting industry that thrives in all parts of the world today. Lee himself, however, was compelled by lack of support at home to seek patronage from the French king Henri IV. Owing to the opposition of the hand-knitters the knitting-machine only slowly established itself in the seventeenth century.

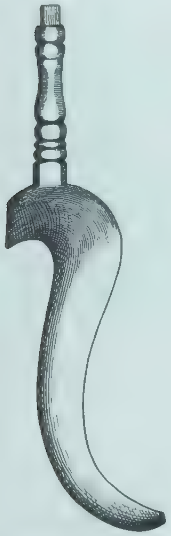


FIGURE 121—*A simple knitting-stick.*

One other knitted fabric must be mentioned, namely felted knitting, which played an important part in the development of headgear from pre-Tudor times. The felt was made by soaking a piece of knitted fabric in water and vigorously pummelling it with heavy stones. This loosened the fibres and caused them to mat together, yielding a fabric with a felted appearance used in the Basque country for the production of 'bonnets', later referred to as berets, and for the apprentices' caps worn in Tudor times (figure 122).

A different type of fabric was embossed knitting, a product of Holland, Germany, England, and the Isle of Aran. Embossed fabrics were made by reversing the position of knit and purl stitches in stocking-stitch fabrics, the reverse purl stitches on the stocking-stitch foundation creating elaborate designs. The vest worn by Charles I on the day of his execution (30 January 1649) is a very fine example of embossed knitting (plate 9 C), and a circular piece of eighteenth-century Dutch fabric in the Victoria and Albert Museum, London, has a design in which flowers, birds, and animals have been used to form an incredibly intricate series of patterns.

In France, from the fifteenth century onwards, lace hose formed the principal manufacture of the knitters' guild. The patterns on these hose were copied from hand-made laces; in the Shetlands, where lace-knitting developed during the nineteenth century, the earliest specimens were copied from a collection of laces taken over to the islands by one Jessie Scanlon. An interesting knitted specimen dated 1840 in the Victoria and Albert Museum shows a combination of embossed and lace knitting. The rectangular centre is a prayer for the High Court of Parliament worked in reverse stocking-stitch foundation. The border is a very fine example of lace knitting.

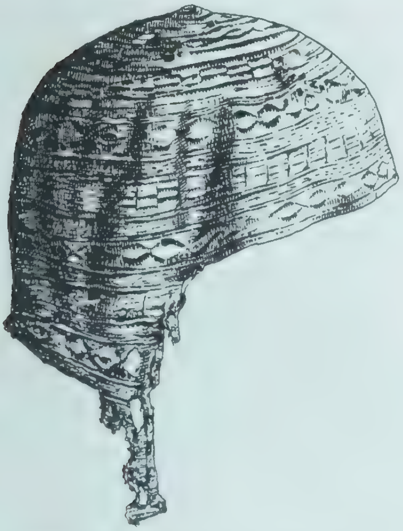


FIGURE 122—*Tudor cap of knitted and felted fabric.*

At the present day the domestic art of knitting seems to have returned to its simpler beginnings. Though a great industry manufacturing hose, jersey cloth, and many other knitted fabrics with the aid of complex and expensive machines is now based on the ancient principle of forming a continuous series of loops into a meshed fabric from which hand-knitting originated, millions of women still furnish their families with garments by their skill with knitting-needles, while several makes of simple knitting-machine for home use (of both the circular and the flat-bed types) recall William Lee's invention of three centuries ago and the household stocking-frame industry to which it ultimately gave rise.

8

FIGURED FABRICS

J. F. FLANAGAN

I. THE DRAW-LOOM

THE term 'figured fabric' is often used to denote any fabric ornamented with design produced by weaving, embroidery, painting, printing, or in some other way. To a weaver, the only figured fabrics are those with a design produced on a loom equipped with a 'figure-harness', an apparatus enabling design repeats to be woven in both the width and the length of the fabric. Before the introduction of the Jacquard machine at the beginning of the nineteenth century, this loom was called the draw-loom (p 165).

There are two main kinds of harnesses, the heald-harness[1] and the figure-harness. The former is used for non-figured weaves, such as plain tabby, twill, and satin, and for small pattern-effects such as those of the traditional peasant weaves of Sweden. The object of the heald-harness is to lift or depress warp-threads, so that a passage (shed) is formed through which the shuttle can be passed. This is called a pick of the shuttle. A figure-harness lifts the warp threads as required for the making of the design in the fabric. The draw-loom had the two kinds of harnesses, the figure-harness for the design, and the healds for the binding-weaves of the fabric (figure 123). The weaver's assistant, the draw-boy, controlled the figure-harness either from the top or from the side of the loom. The weaver sat in front of the loom working the healds by means of foot-treadles. With his hands he threw the shuttle through the warp-shed produced by the healds and the figure-harness, and beat the weft into the fabric with a shed-stick, comb, or reed.

II. THE FIGURE-HARNESS

The figure-harness that was in use at the beginning of the seventeenth century was composed of tail-cords, pulley-frame, neck, comber-board, and couplings with mails and lingoes (figure 124). The pulley-frame was over the top of the loom. It contained a few hundred pulleys, which served to divert the tail-cords from a vertical to a horizontal direction. The comber-board was a few feet below

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[1] Heald and heddle are two forms of the same word. Heddle is used in Vol I, e.g. p 426, figure 269 and in Vol II, ch 6 for relatively simpler looms. It became the favourite term for this purpose, perhaps because of its assonance with the treadle which sometimes worked it. For the fabrics treated in the present chapter, the term heald is needed.

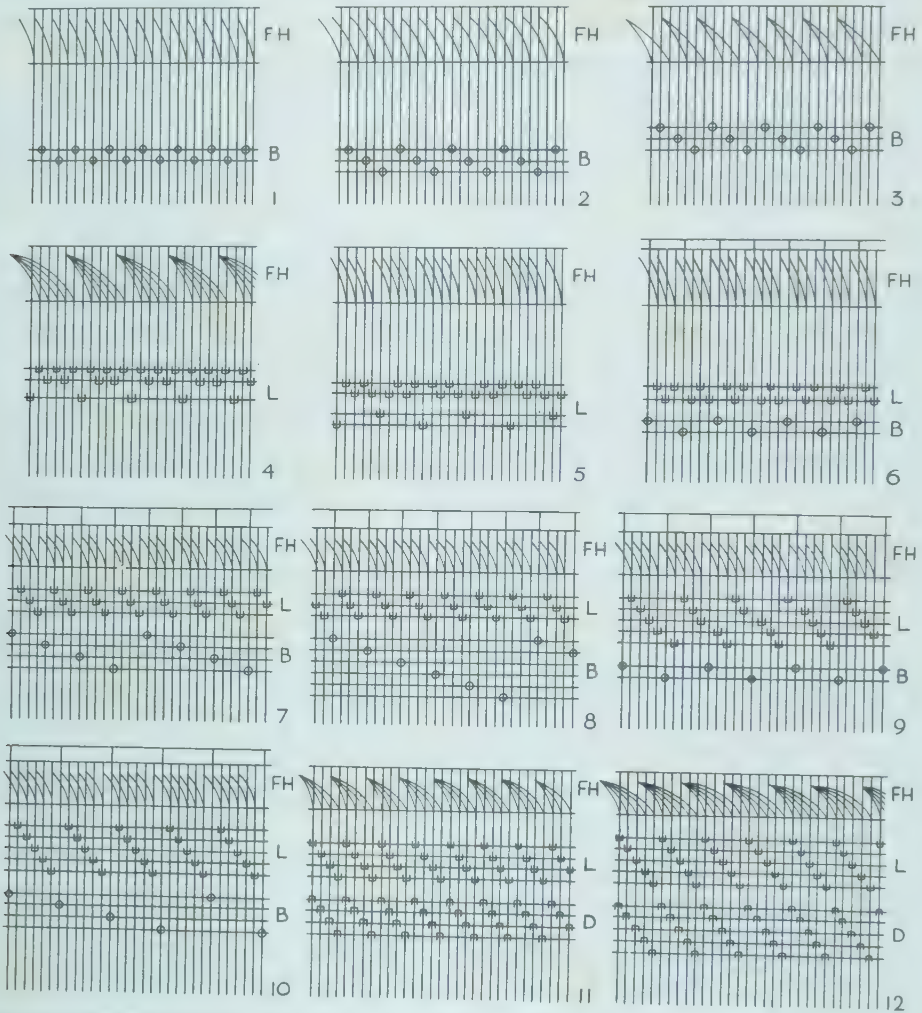

FIGURE 123—*Diagrams showing plan of warp and healds in the loom.* (1) *Weft-faced figured tabby;* (2) *weft-faced figured twill;* (3) *weft-faced figured twill: the drawcords control the figure-harness warp-threads in pairs for 'scaling';* (4) *early tabby tissue, with one binder-heald for tissue-binding;* (5) *tabby tissue with two binder-healds for tissue-binding;* (6) *tabby tissue* (diasprum) *with two healds and binder-warp for tissue-binding;* (7) *twill ground tissue with four healds and binder-warp for tissue-binding;* (8) *twill ground tissue with six healds and binder-warp for tissue-binding;* (9) *satin ground tissue with two healds and binder-warp for tissue-binding;* (10) *satin ground tissue with four healds and binder-warp for tissue-binding;* (11) *twill damask with four-heald binding;* (12) *satin damask with five-heald twill-binding.* (FH = *Figure-harness cords;* D (⊓) = *Depression-healds;* L (⊔) = *Lifting-healds;* B (○) = *Binder-warp healds.*)

the pulley-frame. It was perforated with small holes, one for each neck-cord to pass through. Its purpose was to extend the harness to the full width of the warp. The converging of the neck-cords between the comber-board and the ends of the tail-cords under the pulley-frame made the 'neck'. The coupling was composed of top and bottom halves, and a metal mail connected them. The top of the coupling was tied to the end of a tail-cord, six inches or more below the comber-board. The warp-ends passed through the eye of the mail. A wire weight, six inches or more in length and usually of lead, was tied to the bottom end of the coupling. This weight is called a lingoe. It served to keep the harness-cords taut, and to bring the warp-threads back to the position of rest after being raised. The neck-cords and couplings were more numerous than the tail-cords. If there were four figures in the width of the harness, there would be four neck-cords to each tail-cord. Therefore by pulling a tail-cord one warp-thread of each figure would be lifted. The great advantage of the neck was that the number of cords controlled by the draw-boy was much less than the number of warp-threads in the warp. Thus for a harness with 1600 mails and four figures only 400 tail-cords would be required. The inventor of the neck made a very valuable contribution to the construction of the figure-harness.

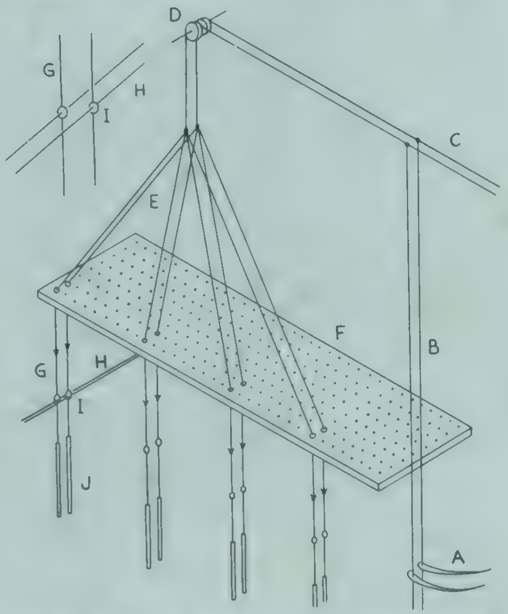

FIGURE 124—*The principles of the construction of the figure-harness with neck.* (A) *Lashes;* (B) *simples;* (C) *tail-cords;* (D) *pulleys;* (E) *neck-cords;* (F) *comber-board;* (G) *coupling;* (H) *warp-threads;* (I) *mails;* (J) *lingoes.*

It is believed that, in 1606, Claude Dangon of Lyons imitated the Italian draw-loom (p 165) and added simples and lashes (*semples* and *lacs*). Simples are cords stretched from the tail-cords to a rod fastened to the floor at the side of the loom. The lashes are loops which were laced round the simples, and agree in number with the tail-cords to be pulled for each figure-pick. The lashes for a single lift of the harness were assembled and tied with a knot. For a long design there were thousands of such knotted lashes. The introduction of the simples made it possible for the draw-boy to stand on the floor at the side of the loom instead of being over the top of it (figure 100).

There is not much information available concerning figure-looms earlier than the seventeenth century. There are no medieval illustrations of them. The fact that simples were added to the harness at the beginning of the seventeenth century helps us to obtain some idea of the stage in development up to the previous century. Besides the loom with Dangon's simples, there was one with drop-shaped buttons for the controlling of the harness-cords. This is said to have been invented by Jean le Calabrais in the fifteenth century. Lashes were laced round the tail-cords, and a knot of them had a single cord which was passed through a hole in a board. A drop-shaped button was attached to the end of the cord. By pulling a button the warp-threads were lifted for a figure-pick. The number of buttons would agree with the figure-picks required to make the design. This method was not suitable for large designs, as too many buttons were required. It is believed that a neck-harness was used for this loom, but it is doubtful whether the neck was in use much earlier than the fifteenth century (figure 125).

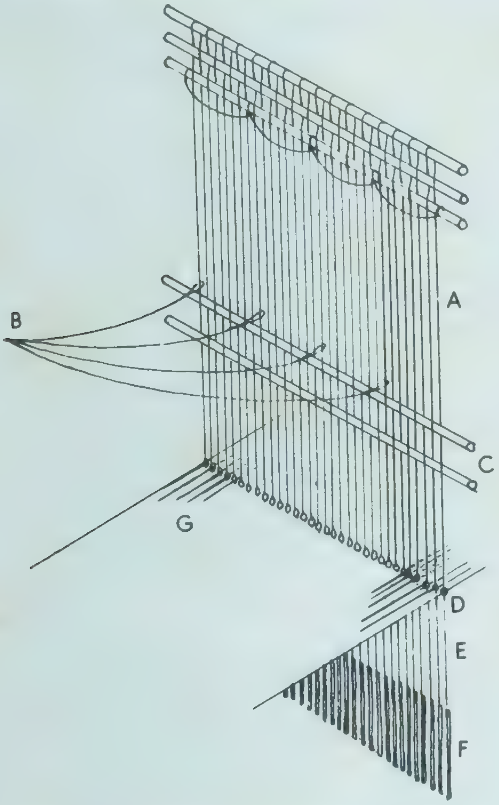

FIGURE 125—*Probable arrangement of the early figure-harness without neck.* (A, E) *Harness-cords;* (B) *draw-cords: one cord to each harness figure or repeat;* (C) *cross-sticks to keep the harness-cords in correct order;* (D) *harness-mails;* (F) *wire weights to keep the harness-cords taut;* (G) *warp.*

The Chinese draw-loom (figure 126) has a figure-harness without a neck, comber-board, pulley-frame, or tail-cords. The draw-girl sits over the loom behind the figure-harness. The draw-cords pass over her right shoulder. Since the harness has no neck- or tail-cords, a set of loops or lashes would be required for each figure of the harness, instead of only one for a harness with a neck. The figure-harness in use in Europe in the early medieval period must have been similar to that in the Chinese drawing.

III. FORMATION OF THE DESIGN ON THE DRAW-CORDS

All figure-harnesses are composed of sections, one section to each repetition of the design. Each section is called a figure, and for that reason the weaver describes the design-repeats as figures. The design, as distinguished from the background, is also called the figure since it is produced by the operation of the figure-harness. In the building or mounting of a figure-harness, alternate figures are sometimes reversed. The kind of harness thus created is called a point-harness, the actual point being the point where the reversing begins and ends. The point-harness produces turn-over designs, such as those with confronting or addorsed animals and birds in roundels on many medieval silks. From the turn-over designs on some early figured silks, we can understand that a figure-harness without a neck was used. The figure-harness with a neck reverses all the details of the design. With a neckless figure-harness it is possible to reverse only a portion of the design. This is clearly shown, on the tenth century Saint-Josse 'Elephant' silk (plate 10 A). This silk has an Islamic inscription giving the name of a ruler of Khurasan. The elephant and other details of the design reverse, but the inscription does not. The same occurs on a thirteenth-century silk at Lyons, and on other silks without inscriptions some details are not reversed. The loom used for these Islamic silks would be the same as that on which contemporary Byzantine silks were woven. It is therefore certain that the early European figure-harness had no neck.

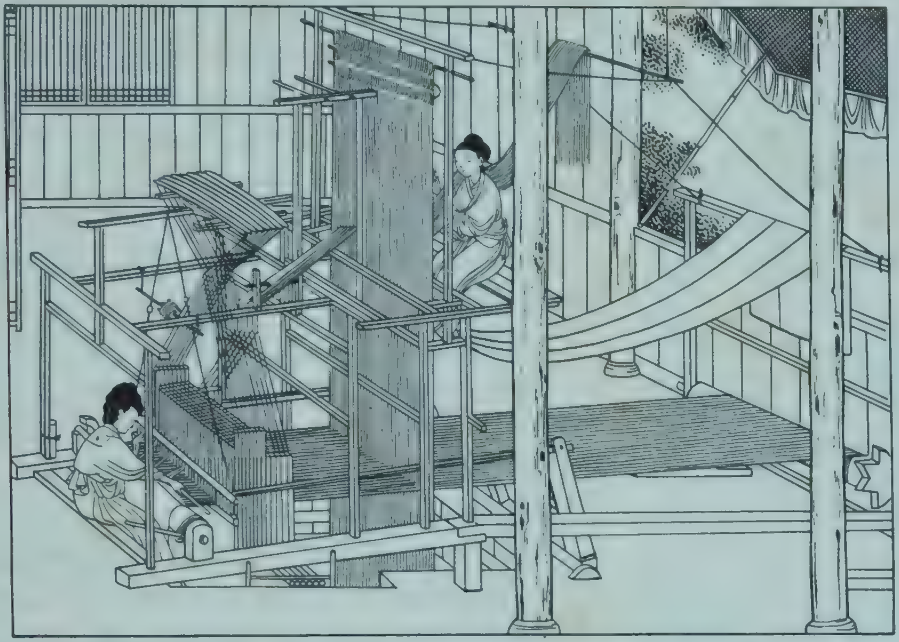

FIGURE 126—*Chinese draw-loom, seventeenth century. Although the weaver* (left) *is passing the shuttle through the shed, neither the figure-harness nor the healds are forming the shed. There are other technical inaccuracies in the artist's drawing.*

In the drawing of the Chinese loom two sets of healds are shown in front of the figure-harness, one set of five healds lifted by gibbet-levers, and one of eight depression-healds. The five healds would be used for making satin-ground weave. The eight depression-healds would be used for the binding-weaves of the design. Italian looms of the late fourteenth and the fifteenth centuries had the five lifting-healds for satin-ground weave, and as many as six for the binding of figure-wefts. The depression-healds of the Chinese loom are hung from rods with sufficient elasticity to retract the healds after depression. The European depression-healds did not have such rods. They were hung from weighted levers (figure 127). Spanish looms of the same late medieval period had the five lifting-healds for satin but fewer for the figure-binding.

Scaling. It was possible to increase the scale of the design by controlling the harness-cords in groups of two or more, or by entering two or more warp-threads through each mail. A cloth with 50 warp-threads to the inch, and with a design eight inches in width repeat, would require 400 harness-cords. If the harness-cords were controlled in pairs the width of the design-repeat would be extended to sixteen inches. This principle was understood by Byzantine silk-weavers as early as the seventh century. Scaling produces a horizontal stepping round the design-contours (plate 10 B).

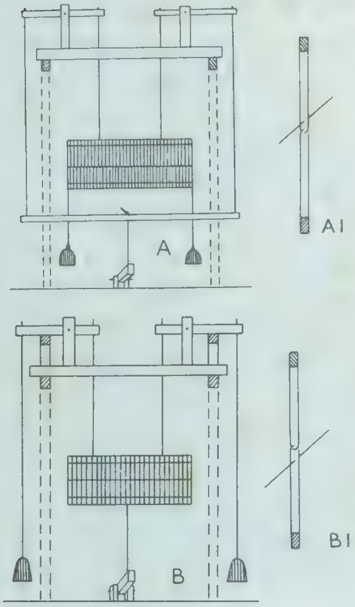

FIGURE 127—*During the last two or three centuries the above methods of lifting and depressing healds have been used, but, as there are no representations of medieval draw-looms, it is not possible to say when they were first used in connexion with figure-weaving. It is certain that similar methods would be necessary for the control of a number of healds.* (A) *Method of lifting healds by wooden levers;* (A I) *the warp end is entered through the top loop of the heald-harness thread;* (B) *method of depressing healds by wooden levers;* (B I) *the warp end is entered through the bottom loop of the heald-harness thread.*

Figure-picks were sometimes repeated in order to economize in the number of lashes. This gives a vertical stepping round the design-contours, a feature that occurs in some of the earliest figured fabrics (plate 10 B).

Dual control of warp-threads. The warp-threads in the Chinese loom would be entered through the figure-harness mail and through the loops of the five healds, also perhaps through the loops of the eight healds. This method of warp-control was practised in Europe before the middle of the medieval period. It was used for tissued silks and damasks. It is a difficult method, as the warp-threads are lifted and depressed by the figure-harness and the healds. This requires much space between the figure-harness and the cloth, and the shed or passage for the shuttle is thus very limited.

Brocading is the introduction of extra weft into only a part of the warp-shed to enrich some details of the design. Gold thread was much used as a brocade weft.

IV. SETTING THE DESIGN ON THE HARNESS-CORDS

In order to reproduce the design on the cloth by lifting some warp-threads and leaving others down, as required to make the correct shed for the design-pick, it was necessary to select the particular cords to be pulled or drawn. During the past few centuries the design has first been painted on point-paper, the number of squares agreeing vertically with the tail-cords or simples, and horizontally with the figure-picks. The horizontal rows of the point-paper were 'read' by one person and the lashes 'laced' on the tail-cords or simples by another (figure 128). It seems likely that point-paper was used at least as early as the fifteenth century. For patterns to be worked in cross-stitch embroidery it was certainly used a little later. We can only surmise what method was used in the early period of draw-loom weaving. It is possible that the design was laced directly on the draw-cords without any other aid than the original drawing. Later, but before the invention of printing, the design was probably ruled out in squares by the designer. When draw-loom weaving was first practised in Roman Egypt or Syria, a considerable amount of tapestry-weaving was being produced by direct methods. We know that these tapestries were sometimes woven in conjunction with draw-loom weaving (plate 10 C). In India as late as the present century designs for figured silks were placed directly on the cords without the aid of a point-paper drawing. The Indian figured-silk weaving tradition is of Persian origin, and the Persian methods derive from the same early medieval beginnings as the early Byzantine.

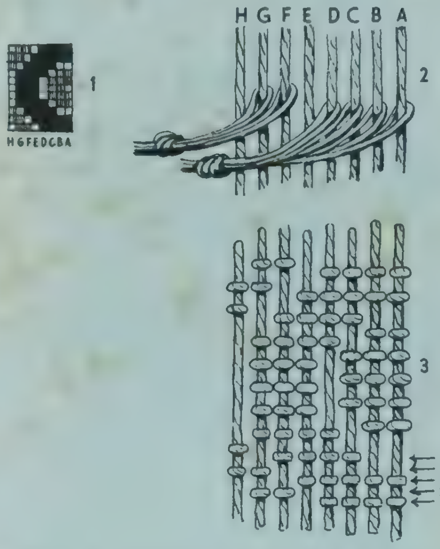

FIGURE 128—*Method of 'reading' or setting the design on the simples.* (1) *A small point-paper drawing for a design in two wefts;* (2) *the lashes on the simples for one line of the drawing;* (3) *the back of the simples showing all the lashes for the design on the paper.*

V. WEFT-FACED FIGURED FABRICS

The earliest figured fabrics so far known to us, excluding those of China, have a surface mainly of weft, and this is true of both the back and the front of the material. The background and the design on the face of the fabric are of the same weave. They have two sets of warp-threads, and in the beginning both were most probably on the one warp-roller or -rod. One set of warp-threads was controlled by some form of figure-harness, the other by healds or an equivalent. We say some form of figure-harness because in the first place the form must have been very elementary. Also, for the earliest of these fabrics, the weft-faced tabby, a shed-stick might have been used for the making of one of the two sheds required for tabby. The figure-harness warp was used only for producing the design, and the other warp for the binding-weave of the fabric. The figure-harness warp is hidden, sandwiched between the wefts at the back and the wefts at the front. It served to keep at the back the wefts that were not required on the front of the fabric for the design. It cannot be called a ground-warp because it does not make the ground-weave. There were two early weft-faced fabrics, the figured tabby and the figured twill.

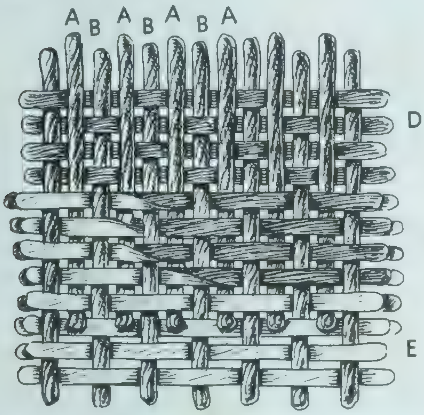

FIGURE 129—*Weft-faced figured tabby weave.* (A) *Warp controlled by drawcords;* (B) *warp used for binding the weft;* (C) *the warp and the two wefts;* (D) *the weave with the face-weft removed:* (E) *the same with the face-weft and binder removed.*

Weft-faced figured tabby (figure 129). It is believed that the earliest fabrics in this weave so far noticed are not earlier than the third century A.D. They are woven in wool, or in wool and linen. A great number have been found in Egyptian graves of the late Roman and early Byzantine periods. Many are ornamented with small designs, resembling in some cases the small filling designs on Roman pavements. The draw-cords for some of these designs would be very few and therefore only a very elementary form of figure-harness would be required. It has been suggested by some writers that the smallest designs might have been woven by a few healds without the use of draw-cords. That is very improbable. It is necessary to take into account the whole group of these fabrics, including those with larger designs, some of which are ornamented with Hellenistic hunting scenes, requiring a great number of draw-cords. It appears that these early draw-loom fabrics, many examples of which have been found in Egypto-Roman graves, were woven by tapestry-weavers using a primitive technique. One of these fabrics, ornamented with a kind of pavement-design in draw-loom weaving, has two panels of tapestry which were woven by the same weaver and at the same time as the draw-loom portions (plate 10 C). The evidence indicating the use of draw-cords lies in the small accidental faults, which recur in each width-repeat of the design. The designs on many of these figured wool-stuffs are so arranged that, to be correctly viewed, the warp-threads must be horizontal and the weft-threads vertical. The cord at the edge of the fabric shown in plate 10 C, which was woven in this manner, is not part of a selvedge, but is the result of twisting the ends of the warp-threads. Tapestry-weavers sometimes treated their designs in the same way, as many Egypto-Roman tapestries show. From the late medieval period it has been the custom to weave most tapestries so that when they are hung the warp-threads are horizontal. This arrangement of design also occurs on a number of figured silks in the weft-faced weave, both the tabby-bound and the twill-bound (plate 12 A). The weft-faced figured tabby was produced in silk for the first time about the fifth century. Chinese weavers wove a figured silk, a multicoloured rep or warp-rib, at least as early as the beginning of the Christian era. Many examples have been found in Chinese Turkestan and southern Mongolia. A few fragments of this Chinese silk have also been found at Palmyra and one or two localities in the west. If the Chinese multicoloured rep and the western weft-faced figured tabby are examined together, one with the warp-threads vertical and the other with the warp-threads horizontal, they appear to be almost identical in weave. This does not signify any technical relationship. The Chinese silk is of warp-effect and the western of weft-effect. The loom used for the one would not weave the other. The technical development was independent. Early in the present century it was assumed, without any consideration of the techniques, that the weaving of figured silks passed from China to Persia during the Sassanian period (226–651) and later to the Byzantine Empire. This assumption was partly due to the fact that the Persians were the intermediaries in the trade in raw silk between the east and the west, before sericulture began in the Byzantine Empire about the middle of the sixth century. Towards the end of the next century the western weft-faced method passed to China, both the figured tabby and the figured twill. Two important early western weft-faced figured tabby silks are the 'Striding Lion' from Antinoë (Antinoöpolis) (plate 11 A) and the 'Maenad' silk at Sens (plate 12 A). After the sixth century few silks were woven in this weave as it was replaced by the figured twill.

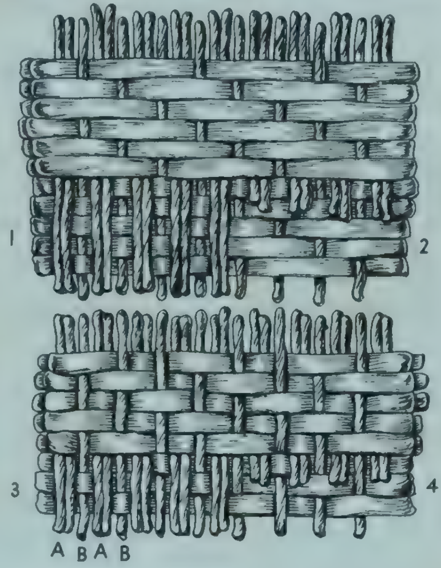

FIGURE 130—*Weft-faced figured twill weave.* (1) *With face-weft removed;* (2) *with face-weft and figure-harness warp ends removed;* (3) *with back weft removed;* (4) *with back weft and figure-harness warp ends removed.* (A) *Figure-harness warp ends;* (B) *binder warp ends. The top drawing shows the front and the bottom drawing shows the back.*

Weft-faced figured twill (figure 130). This was a development of the weft-faced figured tabby. Three healds, instead of two, were used for the binding. In the thirteenth century four healds were used for some silks in this weave. No doubt twill was used instead of tabby because it gave a longer weft-float and therefore the pattern effect was more solid; and because, the cloth being finer in silk than in wool, it required a looser binding-weave. There are some early examples with the twill-binding in wool, but these are coarse fabrics. The weft-faced figured twill (the early Byzantine figured twill) was the chief figured silk fabric during the first half of the medieval period. It began in the Near East, probably in Syria or Egypt. Some of the major works were made in Constantinople about the tenth century. The 'Elephant' silk from the shrine of Charlemagne at Aachen, with roundels 30 inches in diameter, and the great 'Striding Lion', were made there (plates 11 A, B). Later this weave was practised in Spain, Italy, and Germany. After the thirteenth century it was displaced in the older weaving-centres by the new tissue methods, but it survived in Germany as late as the sixteenth century. In the fifteenth, it was employed for the making of orphreys and other ecclesiastical ornaments (plate 12 C). The orphreys have thick linen warp-threads, and their ornamentation includes figures of saints with faces, hands, and so forth worked in embroidery. In some cases the design is so varied and unrepetitive that it is doubtful whether a figure-harness was used.

A very considerable number of fragments of silk in this weft-faced figured twill have survived, many of them in countries where they were not woven, such as France, Belgium, Holland, England, and Spain. Those which have been preserved in Germany are mostly of the kind that were not made there. They served largely for the wrappings of holy relics, ecclesiastical vestments, and royal robes. Many have been preserved made up into seal-bags. At Canterbury there is a large collection of early medieval examples. Durham has a few very important ones. At Westminster Abbey there are many small fragments, mostly of seal-bags and not so early as the earliest of Canterbury and Durham. On the Continent there are more important collections at the Vatican City, Sens, Maastricht, Cologne, Milan, and many other places. No other weave has served for so many major works or for such a variety of interesting motifs.

VI. TISSUED FABRICS

The mature tissued fabrics were first produced about the twelfth century. They have two warps, a ground-warp and a binder-warp. The ground-warp and the ground-weft make the foundation-weave of the fabric. As the ground-warp predominates over the ground-weft, the weave is said to be of warp-effect. For most of the medieval tissues the ground-warp threads are in pairs in the mail. The figure-wefts (called the tissue-wefts) are bound by a binder-warp. Thus there are really two webs, one composed of the ground-warp and the ground-weft and the other of the binder-warp and the tissue-weft. The two webs combine to make one fabric, since the tissue-wefts pass to the front and the back of the fabric as required for the making of the design. The ground-pick is not a figure-pick, as the figure-harness does not help to produce the shed for it. The ground-weave is really a plain foundation cloth of either tabby, twill, or satin. The weaver makes it with the healds alone. If he lifts the whole of the binder-warp when making the ground-pick, a pocket occurs between the two webs.

In making the weft-faced figured fabrics the healds were required only for the control of the binder-warp; for the tissued fabrics, however, an extra set was required for lifting of the ground-warp. The ground-warp threads passed through figure-harness mails and through the top loops of the ground-warp healds. This dual control of the ground-warp was a new principle in figure-weaving, and a very important one. In the weaving centres where it was practised the older, weft-faced method was abandoned. After the thirteenth century, dual control of the ground-warp was more complicated, but the pace of weaving was increased. Its great advantage was that the warp-effect ground and weft-effect tissue gave more variety in texture. The weft-faced fabrics had only weft-effect.

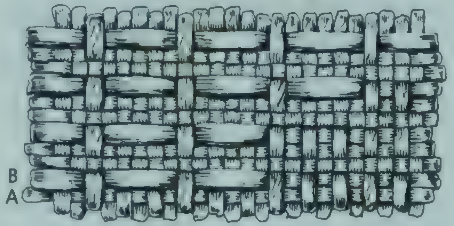

FIGURE 131—*Early tabby tissue with one heald (or its equivalent) for the tissue-binding by every sixth warp thread.* (A) *Ground-weft;* (B) *tissue-weft.*

Tabby tissue. The tissue method did not begin in the twelfth century. In an immature form it existed about five centuries earlier. It has its origin in a woollen fabric brocaded with linen, without the use of a figure-harness. The ground weave is tabby. This wool-and-linen brocade fabric is one of the many varieties found in Egyptian graves of the Roman period. About the seventh century A.D. silk was used instead of wool and linen, and the design was made with a tissue-weft instead of brocading. Some of the wool-and-linen brocades have design-binding by every fourth warp-thread, others by every sixth warp-thread. The same occurs on the earliest silk tissues; one at Saint-Moritz, Switzerland, is bound by every fourth warp-thread, and two at Durham and another at Utrecht by every sixth warp-thread (figure 131). The fragments at Durham, found in the coffin of St Cuthbert (? 635–687), are the largest and best preserved. Those at Utrecht were parts of the vestments of St Willibrord (*c* 657–*c* 738), a younger contemporary of St Cuthbert. Examples of about the tenth and the eleventh centuries, mostly Islamic, have the tenth or the twelfth warp-thread as the design-binder. These early tabby-ground tissues had a single warp, and the figure-binding required only one heald. Because there was only one heald for the tissue weft-binding, it was necessary to have two ground-picks to each tissue-pick, otherwise the tabby ground would be imperfect. The single-heald binding produced an unpleasing striped effect, rendering the weave less attractive than weft-faced fabrics. About the eleventh century two healds were used for the tissue-binding, and this gave a satisfactory tabby-binding to the tissue. With two healds only one ground-pick was required to each tissue-pick. In the next century a second warp, a binder-warp, was introduced to make the tabby-binding of the tissue: a great advantage as it helped to make a more attractive fabric. Previously these tabby tissues were self-colour, the warp and the weft being of the same colour. It was now possible to have tissue-binders of a different colour from the ground-warp. The tabby tissue with a binder-warp, called *diasprum* (jasper), is the first mature tissue (figure 132). One of the earliest *diaspra* is the robe from the tomb of the Emperor Henry VI (d 1197) at Palermo (plate 12 B). The tissue-weft is of gold thread, the ground now a dull rose silk. For some of the early *diaspra* more than one tissue-weft was used, as in a Spanish example (plate 13 A). Most of these fabrics are brocaded (plates 13 C, D).

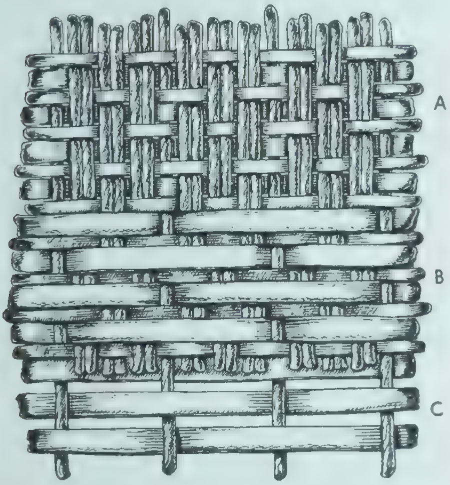

FIGURE 132—Diasprum-*weave.* (A) *Ground-weave with figure-weft at the back of the cloth;* (B) *figure-weave with figure-weft at the front of the cloth;* (C) *showing ground-warp and ground-weft removed from the front of the cloth.*

In the late eleventh and early twelfth centuries some attempts were made to produce the effect of tabby tissue on the loom used for the Byzantine figured twill. For this the whole of the figure-harness warp was lifted to give one tabby-shed, and the whole of the binder-warp to give the other. This made the background weave, the figure-pick being made by the usual weft-faced twill method. Among the silks so woven are a material said to have been part of the robe of the Emperor Henry II (973–1024); part of a vestment supposedly worn by St Bernard of Clairvaux (1091–1153); and a material from the shrine of Edward the Confessor (? 1002–1066). The shroud of Saint Siviard (d 687) at Sens Cathedral is a combination of tabby tissue and Byzantine twill.

Twill-ground tissues (figures 133, 134). With three healds for the ground-weave in place of the two for the *diasprum* weave, the three-heald twill tissue

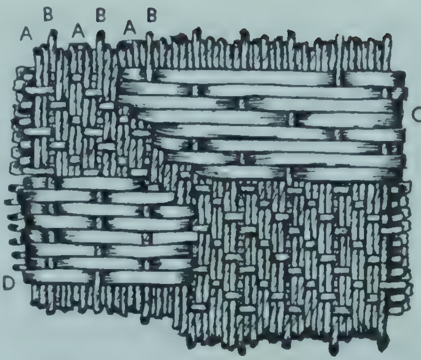

FIGURE 133—*Warp effect twill-ground tissue, with tabby and four-end twill figure-binding.* (A) *Ground-warp;* (B) *binder-warp;* (C) *four-end twill tissue-binding;* (D) *tabby tissue-binding.*

was possible. It is not unlikely that this new European figured weave was inspired by the twill and the satin ground-tissues from China which had spread to Near Eastern Islamic countries about the end of the thirteenth century. Some of these oriental silks were found in a fourteenth-century tomb at Verona in 1921. Secondhand renderings of Chinese motifs and the free treatment of Chinese designs occur for the first time in Europe on the fourteenth-century north Italian twill-ground tissues (plate 13 B). This eastern influence in western design contrasts strongly with the more static treatment of pre-fourteenth-century western design. It is believed that many of the Italian twill-ground silk tissues were made at Lucca. They are often referred to as Lucchese fabrics. Twill-ground tissues were also made in Spain. The Italian weavers used more healds for the tissue-binding than were used elsewhere. Four-heald twill tissue-binding was common. Another tissue-binding was a special form of a six-heald weave (plate 14 A). The twill-ground tissue-weave was not much favoured after the early fifteenth century, when satin and velvet fabrics became more popular. The style of the twill-ground tissues, with numerous varieties of fantastic animals and birds, gave place to a bolder and more static form, better suited to the new damasks and velvets. Perhaps the fact that the dyes used for the twill-ground tissues were not very fast to light helped to put them out of favour.

Satin-ground tissues (figure 135). The minimum number of healds required for a satin-weave is five. There is a four-heald weave, satinet, which is half twill and half satin; it is not a true satin. It occurs in some Islamic fabrics. Twilled fabrics have diagonal lines, from which satin is almost free and therefore has a clearer and smoother surface. Five-heald satin was the only one practised in Europe for the weaving of figured fabrics before the sixteenth century. Satin tissues have a warp-effect satin, and for this more warp-threads are required than for other weaves. The earliest satins have about 200 pairs of

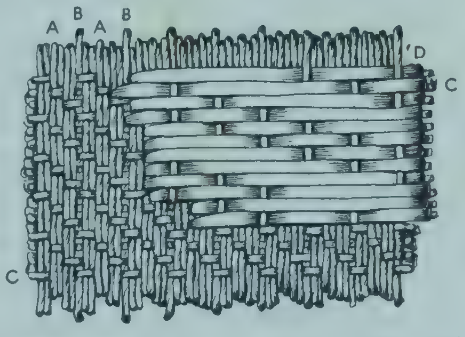

FIGURE 134—*Fourteenth-century Italian twill-ground tissue.* (A) *Ground-warp;* (B) *binder-warp;* (C) *ground-weft;* (D) *tissue-weft.*

warp-threads to the inch. Some European satins woven at the beginning of the present century have as many as 600 single warp-threads to the inch. During the Middle Ages the warp-threads controlled by the figure-harness were generally in pairs. Pairs of threads are not so satisfactory for satins as single threads, but 200 single threads would give a very poor satin. In the fifteenth century Italian silk-weavers, using single threads, increased their number. In the following centuries the number of single ends was further increased in order to make a finer satin.

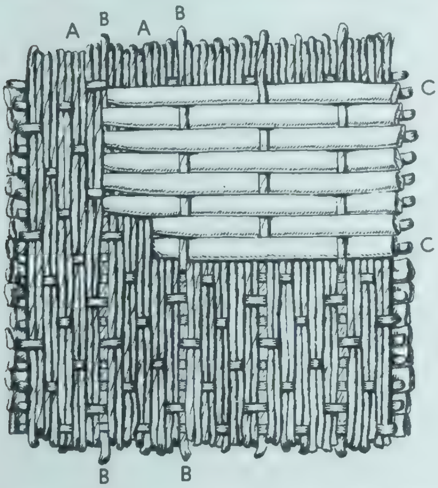

FIGURE 135—*Satin ground-tissue, with tabby tissue-binding.* (A) *Ground-warp;* (B) *binder-warp;* (C) *ground-weft.*

The satin weave is of Chinese origin. Satin tissues and damasks became known in the west about the end of the thirteenth century. The earliest are ornamented with designs composed of a mixture of Chinese and Islamic motifs, including Islamic script. Some have the title *Al-Nāṣir*, appropriated by the late thirteenth- and early fourteenth-century Mameluke sultans of Egypt (*c* 1251–1517). Many of these silks have warp-stripes of various colours, ornamented with Chinese or Islamic motifs including script. The satin-ground tissue-weave was practised in Spain and Italy in the fourteenth and fifteenth centuries. Some of the earliest Spanish examples have the warp-stripes in various colours covered with ornament and script (plate 14 B) showing a continuity of the Chinese-Islamic tradition, but the immediate influence is Near Eastern Islamic and not Chinese. There is none of the freedom of Chinese design which shows so much in fourteenth-century Italian twill-ground tissues. The design style of most of the fifteenth-century Spanish satin tissues is Hispano-Moresque in character (plate 14 C). In northern Italy the satin-ground tissue-weave developed into a fabric which has long been known in Britain as brocatelle. In the sixteenth century, satin made the design and tissue-weft the background, a thick linen ground-weft stiffening the fabric. In the fifteenth century the Italians produced a number of brocatelles with satin backgrounds for use as orphreys. These are ornamented with religious symbols and figure subjects, drawn by artists of repute (plate 14 D). Instead of linen ground-weft, some of these fabrics have thick spun-silk ground-weft. They appear to be the first European fabrics for which spun silk was used.

VII. DAMASKS

Tabby damasks. Damask weaving, especially before the introduction of the Jacquard machine early in the nineteenth century, was a particular method of figure-weaving. Besides the figure-harness and the lifting-healds of the tissue method, a set of healds was required to depress the warp-threads for the binding of the design. In the case of the tissue, the figure was bound by a binder warp. Damasks have only one warp, and therefore the binding of the design as well as the ground was done by the warp, which was also controlled by the figure-harness. The single warp was treble-controlled: by the figure-harness, by the lifting-healds, and by the depressing-healds. This is true of the twill and the satin damasks but not of the tabby damasks. Silks with a single warp and weft, with a ground of tabby and a design in short floats over three, five, or seven warp-threads, may be included as immature damasks, although it is doubtful whether any depression-healds were used in making them.

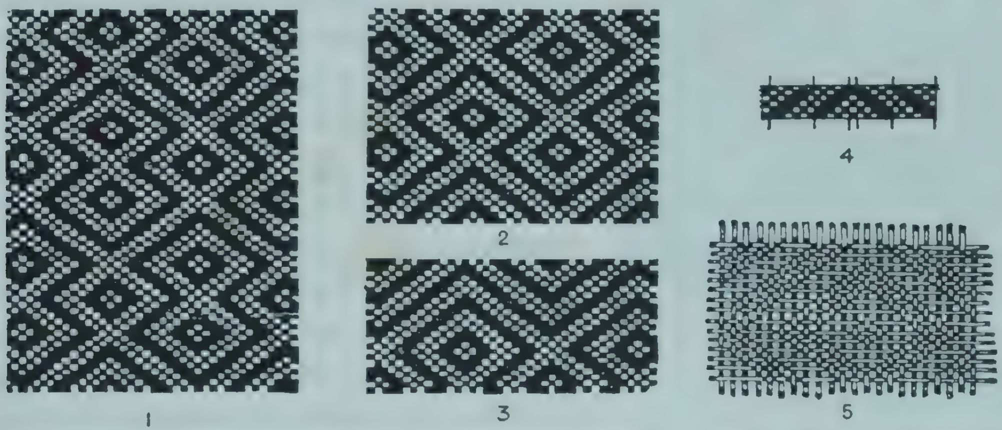

FIGURE 136—*Silk fragments from Kerch (Crimea), probably Chinese, c 100 B.C.–A.D. 100. (1) The main design; (2, 3) variations of the design in the fragments; (4) the unit of the design; (5) diagram showing the interlacing of the yarn.*

Advanced tabby damasks were woven in Spain about the end of the twelfth century and early in the thirteenth. Many have been found in the royal tombs at Burgos, including some with bars of Islamic script in an extra weft. One of these Spanish silks, without the bars of script, was used as a lining material for parts of the vestments of Walter de Cantelupe (1236–66), found in his tomb at Worcester in 1861. The Spanish weavers developed a multicoloured silk from the tabby damask, but it did not long remain in favour. The tabby damask is of Chinese origin. Many examples woven in the early centuries of the Christian era have been found in Chinese Turkestan. One of the earliest, found in a Graeco-Scythian grave at Kerch in the Crimea (figure 136), is thought to be at least as early as the beginning of the Christian era. Another, from a tenth-century grave at Birka, Sweden, is believed to be Chinese, but this kind of weaving may have passed to western Asia before that date. It must have reached Spain from some eastern Islamic country.

It is difficult to determine the method of weaving these tabby-ground silks. Some could be produced on a loom with a few healds without the aid of a figure-harness. The Crimean example would have been possible on six healds. However, we have to take into account the large number which could not be woven without some form of draw-cord, such as that from Birka, the Spanish examples, and many of the Chinese. Their designs would be impossible with healds alone. The most probable method was with two healds (or their equivalent) for the tabby ground and draw-cords for the design. By draw-cords we mean some elementary form of figure-harness. The two healds would serve as lifting-healds for the tabby.

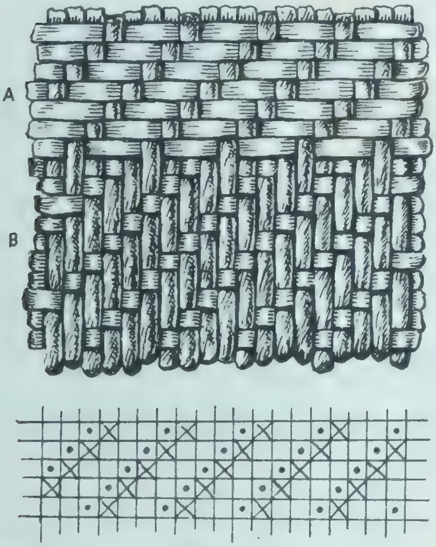

FIGURE 137—*Four-end twill damask.* (A) *Weft effect, for the design;* (B) *warp effect for the ground;* (●) *lifted-ends for the ground-weave;* (X) *lowered ends for the design-weave.*

Twill damasks. There are many kinds of twill damask. Three-heald, four-heald, and six-heald damasks are among the silks found in Chinese Turkestan by Sir Aurel Stein (1862–1943). Four-end twill (figure 137) and tabby occur in the same material; six-end and three-end twills also occur together. Four-end twill ground and four-end twill figure are found in some damasks preserved in Europe. One of these is the silk said to be the dalmatic of St Ambrose (? 340–97), at Milan. Another is in the treasury of the church of St Servatius at Maastricht (plate 15 A). There are also a few fragments, with small designs, in this weave at Sens. The Milan silk has a Hellenistic hunting-scene on it; that at Maastricht has a large roundel setting, with border ornamentation of formal foliage motifs similar to those found on some early medieval silks in the Byzantine figured twill. It is impossible to believe that these western twill damasks were woven at the beginning of the Middle Ages. One cannot but suspect that they are twill-damask renderings of silk designs originally woven in the weft-faced figured-twill weave. Twill damask is a very advanced weave. It must have been considerably more economical to weave than the weft-faced materials, and a more useful fabric. It is most surprising that only these few examples exist. A four-heald damask with a very small design makes the background of the fourteenth-century Catworth embroideries in the Victoria and Albert Museum, London. Another with a similar design is attached to the shield of Henry V in Westminster Abbey. These may be Chinese, for they are similar to some contemporary Chinese examples. There is at least one other with a western design; it is either Italian or Islamic.

Satin damask. Of the many kinds of satin damask only one was made in Europe before the sixteenth century, the five-heald type (figure 138). The method of weaving satin damask was an extension of the twill method, with the use of more healds. Two sets of healds were required, one for lifting the warp-threads and one for depressing. With the use of more healds the distance between the figure-harness and the fell of the cloth became greater. The strain imposed on the warp-threads by the figure-harness, the lifting-healds, and the depression-healds was considerable, therefore it was more easily possible to weave these damasks with silk warp-yarn than with any other, owing to the great strength and elasticity of silk. No form of weaving called for greater care in the adjustment of the harnesses, for which an elaborate system of lever-control was necessary. Technical knowledge was gained by trial and error.

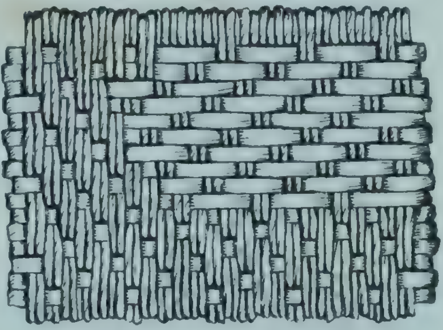

FIGURE 138—*Five-end satin damask.*

Like the tabby and twill damasks, satin damask is of Chinese origin. It became known in the west about the end of the thirteenth century. One of the earliest has Chinese cloud forms and Chinese characters for 'felicity' and 'longevity'. Another bears the name of a Mameluke sultan, Muḥammad ibn Qalā'ūn (1293–1341). Since the fifteenth century Italy has been famous for silk damasks. There is no Chinese influence in the designs on the early Italian damasks; they are mainly in the same Italian style as the contemporary velvets. Like the velvets, some of them are brocaded with gold thread. This further complicated the weaving by necessitating an extra set of depression-healds, the brocade-weft being bound in longer floats than the damask-weft (plate 15 B).

VIII. VELVET

Figured velvets. Velvet differs from other silk fabrics in that the whole or part of its surface is of pile, either cut or uncut. The uncut pile or terry is merely a loop. Figured velvets usually have the design of pile and the ground of a tabby or satin foundation-weave (figure 139), but there are many exceptions. The velvet loom has two warps, one for the foundation-weave and the other for the pile. Some brocaded velvets require a third warp for the binding of the brocade-weft. Unlike most figured fabrics, velvets are woven face-up, rendering brocading less convenient. The pile is made by the insertion in the shed of a wire in place of the usual weft-yarn. There are usually three foundation-picks of yarn. This arrangement is necessary to bind the pile firmly in the foundation-web of the fabric. The pile warp-threads are lifted for the insertion of the wire as required to make the design in pile; hence, as only a portion of the pile-warp is lifted, the take-up of the pile-warp into the cloth is uneven. For the weaving of plain velvet it is possible to have all the pile-warp on a single roller, as it is taken up into the cloth uniformly. For figured velvet each pile warp-thread is wound on a separate bobbin, each bobbin requiring a small weight to keep the thread taut; the single roller also requires weights for the same purpose. The small bobbins are placed on a frame called a creel. The creel is fixed behind the figure-harness, under the foundation-warp. It holds hundreds of full bobbins. The wire for cut pile has a groove in it, that for uncut pile is plain. The groove guides the knife that cuts the loops. The weaver does the cutting while the cloth is in the loom, with an instrument called a 'trevette', and draws out the wires. To roll velvet round the cloth-roller as other fabrics are rolled would damage the pile, therefore a special contrivance for gripping the velvet sufficiently to hold it on the roller is used. The weaving of velvet on the traditional hand-loom is a very slow process.

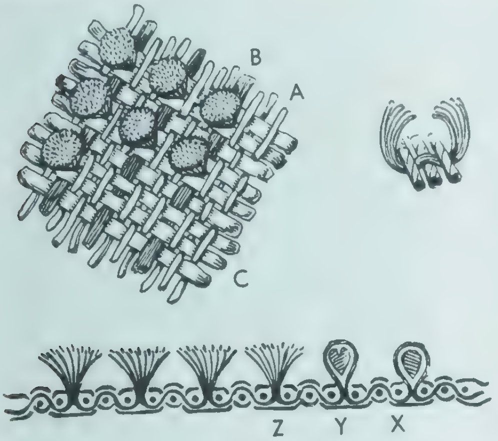

FIGURE 139—*Figured velvet with tabby foundation.* (A) *Foundation-warp;* (B) *pile-warp;* (C) *foundation-weft;* (X) *uncut loop for terry or uncut pile;* (Y) *uncut loop with grooved wire for guiding cutter;* (Z) *cut pile. (The pile tufts* (inset) *are reduced comparatively in order to show the foundation weave.)*

The invention of figured velvet must have required much imagination and ingenuity. The apparatus was designed to overcome the many difficulties in the making of this rich fabric: the creel carrying the separate bobbins for the pile-warp; the wires for the making of the rows of loops; the trevette for the cutting of the loops; and the special cloth-roller. The apparatus illustrated in excellent engravings in the eighteenth-century *Dictionnaire des Sciences* (1765), although of a much later date, was probably very similar to the fifteenth-century equipment capable of performing exactly the same work. Unfortunately we know of no fifteenth-century illustrations of velvet looms.

It appears that figured velvet was woven in northern Italy during the second half of the fourteenth century. One example is said to have been found in the tomb of the Emperor Charles IV (d 1378). There are others with details of design similar to some on the fourteenth-century twill-ground tissues. Unlike so many of the other figured weaves, velvet was not a Chinese invention. Plain velvet, woven some time before figured velvet, was used for background materials for English and continental embroideries early in the fourteenth century. There is reason to believe that it might have been made in Islam before then. Italian figured velvets of the fifteenth century are magnificent and most luxurious. Some have a foundation weave of tabby, others of satin. The foundation tabby of some examples is covered with gold-tissue weft. Cut and uncut pile, sometimes in more than one colour, and also two levels of cut pile, were used to give variety of effect. Many examples are brocaded with *bouclé* gold thread (plate 15 C). In the fifteenth century Italian velvets and damasks were used in churches and palaces throughout Europe; painters delighted to depict saints, churchmen, and nobles draped with them. In England, painted representations of these fabrics on walls served as substitutes for genuine hangings.

Practically all the basic figured weaves were developed in the Middle Ages. What remained to be done later was mainly to extend established principles and to mechanize the processes of manufacture.

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9

GLASS

R. J. CHARLESTON (I–V) AND
L. M. ANGUS-BUTTERWORTH (VI–IX)

In the later Middle Ages glass-making was roughly divided into two spheres—that of the north (including Germany, France, Belgium, England, and Bohemia) and that of the south (mainly Italy). These divisions were based not on geography but on divergent technical traditions. In the north, in the glass-houses surviving in the forested regions after the break-up of the Roman Empire, glass was made with local sands (providing silica) and with the ashes of burnt inland vegetation (impure potassium carbonate) for flux. In the south, silica was frequently obtained by crushing white pebbles from the beds of rivers, while the flux was a soda (impure sodium carbonate) derived from the burning of marine vegetation. These two spheres of glass-making can be conveniently considered separately for the early part of our period.

I. GLASS-MAKING IN THE NORTH (TO ABOUT 1550)

Fluxes. It is not known when the glass-makers of Gaul and the Rhineland, isolated by the political upheavals accompanying the collapse of Roman power, became cut off from their normal sources of soda and fell back on the use of potash. It is certain, however, that by the time of Theophilus Presbyter, in the tenth or early eleventh century, the use of potash was firmly established in the north. In his *Schedula diversarum artium* (book II, ch 1), he says: 'Prepare ashes of beech-wood.' To our present period belongs the work of Georg Agricola (1490–1555) who deals with glass-making in book XII of his *De re metallica* (Basel, 1556). Although Agricola was fully conversant with contemporary Venetian glass-making, and gives it first place in his work, he also reflects the German and Bohemian methods of his time (figure 140). Having treated of the soda-fluxes, he continues:

> But those who have none of the above-mentioned saps take two parts of ashes of oak or ilex or of hard wood (*roborei*) or of turkey oak, or if these are not to hand, of beech or of fir, and mix them with one of gravel or sand, adding a little salt made from brackish or sea water (*aqua salsa vel marina*), and a minute quantity of manganese; but the glass made with these latter is less white and translucent.

In France, bracken-ash was used, and the glass accordingly was called *verre de fougère*.

Furnaces. The use of potash appears to have gone with a predilection for a special type of furnace. The evidence is full of gaps and not wholly consistent, but in general it may be said that a furnace of rectangular plan was favoured, with two to four glass-pots ranged down each side, and with an extension that could be used either for fritting the primary materials or for annealing the finished product. Theophilus, in the work already quoted, prescribes a furnace of rectangular plan, 15 ft by 10 ft, and 4 ft high. This was divided by a wall two-thirds of the way along. Somewhat above the ground was constructed a platform or siege, below which the firing-chamber ran from end to end of the furnace. In the larger chamber there were four holes in the siege down each long side, while holes in the siege in both chambers admitted the heat from below. The smaller part of the furnace was for making the frit. This was prepared with two parts of beech ashes and one of sand, carefully purified from earth and stones; they were mixed together on a clean surface, then roasted over a fire made of thoroughly dried beech-wood. The heated mixture had to be well stirred for a night and a day, to prevent agglomeration. Apart from this, Theophilus prescribes a separate annealing furnace measuring 10 ft by 8 ft by 4 ft.

It is clear, however, that considerable variations of this furnace-pattern were tried in practice. In the work entitled *De coloribus et artibus Romanorum*, attributed to a certain Heraclius, there are in the third book two chapters (VII and VIII) devoted to glass-making. This book was probably added in the twelfth or thirteenth century to the existing tenth-century text. The oven here described has three chambers of unequal size, the central and largest being the working-furnace, with two pots on the siege, the second compartment serving to roast the frit and the third to fire the pots. In a miniature from a fifteenth-century manuscript of 'Sir John Mandeville's Travels', however, a glass-furnace of a slightly different pattern is represented. Here, in the main furnace, there are two pots and two working-holes ('glory-holes') on the side represented, while a smaller, subsidiary furnace is used for annealing, its floor being on the same level as that of the working-furnace (plate 16).

The general arrangement of the rectangular furnace with pots ranged down the two longer sides is confirmed by the ground-plans of late medieval and Tudor furnaces excavated in England, which during this period may be considered a province of France so far as glass-making is concerned. One of the best preserved of these furnace-sites was that at Vann Farm, near Chiddingfold in Surrey, where an earlier glass-house was probably reoccupied in Tudor times.

Here the main working-furnace was an oblong 12 ft by 5 ft 6 in, at the corners of which were four diagonally projecting fan-shaped wings. In these no doubt the heat of the main furnace was utilized for fritting, pot-arching (that is, pre-heating), and annealing. The furnaces were sometimes of stone, sometimes of brick.

Glass-pots. The pots used within these furnaces appear to have been of two kinds. The first was a piriform crucible with an out-turned lip (plate 16), the second a straight-sided pot tapering slightly towards the base. Theophilus (see p 206) gives the following instructions for making a pot: 'Take white pottery clay, dry and pound it carefully, pour water on it, and soften it thoroughly with a piece of wood. Make the pots wide in the upper part, narrow in the lower, and round the mouth form a small lip bent inwards (*labium parvum interius recurvum*).' Fragments of numerous glass-pots of this general shape, but varying in dimensions, have been found on English glass-making sites, and examples with incurved rims attributable to the thirteenth century tend to conform to the description given by Theophilus.

Tools. Of the tools used during this period very little trace is left. The blowing-pipe (plate 16) was rather long, contrasting with the short pipe figured by Agricola (figure 140); like it, however, it has a wooden handle in the upper part, and this seems to be a common feature of the period, as later. Fragments of blow-pipes found on English sites of the fourteenth to fifteenth centuries suggest that the bore varied from about $\frac{1}{4}$ in to about $\frac{5}{8}$ in.

The marver for rolling the glass vesica into a cylindrical form is shown in figure 140. It was no doubt at this period actually made of some smooth stone, if not of marble (as its name suggests).

Moulds for imparting a surface patterning to the glass must already have been in use by the thirteenth century, for vertically ribbed cups and flasks of this century, and even of the end of the preceding one, are known from France and Belgium. In England, many of the glasses of the medieval period are characterized by a close spiral ribbing imparted in the first place by a mould, and in 1535 moulds were among the tools bequeathed by a Sussex glass-maker to his son (figures 140, E, 146, 3).

Otherwise the techniques of making vessel-glass in this period were probably of the simplest, as remaining fragments suggest. Theophilus mentions the processes of blowing, 'warming-in', attachment of the pontil-rod, opening out the vessel, and, for the manufacture of bottles with long necks, swinging of the paraison round the head, the thumb being over the mouthpiece of the blowing-iron (cf figures 140, 147). Threads of glass could be wrought as handles, or trailed on as decoration. These elementary techniques no doubt continued throughout the medieval period. In England, at least, glass of a sealing-wax red was used for ornamentation, and occasionally for complete vessels, probably in the fifteenth century. Blue glass vessels, the colour probably obtained from cobalt oxide, were also being made in England at this date. Until about the sixteenth century, however, vessel-glass was only a by-product of the glass-furnaces of northern Europe, which were mainly occupied with making window-glass (section VIII, pp 237 ff).

II. ITALIAN GLASS-MAKING TO ABOUT 1550

Glass-making in Venice has probably had a continuous existence since Roman times. Little is known of the earliest period there, but in 1090 there is mention of one Petrus Flabianus *phiolarius*, which shows that vessel-glass was already being made. In the thirteenth century the industry was flourishing. By a law of 1291 the glass-works in Venice were moved out to Murano, and it was here that all 'Venetian' glass was made. Enamel glass appears to have been introduced in 1317 and coloured glass for windows by at latest 1330. The most significant of all the Venetian innovations, however, occurred over a hundred years later, namely the making of *cristallo*, a clear crystalline glass.

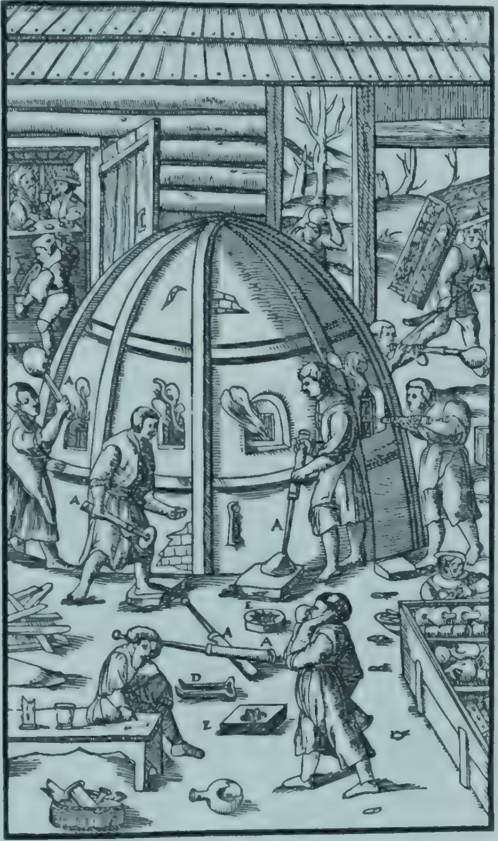

FIGURE 140—*General view of a glass-furnace at work. Note the blowing-irons* (A), *moulds* (E), *pucellas* (D); (foreground) *a woman haggles over the value of a cullet;* (left) *swinging the paraison;* (right centre) *flattening the paraison on the marver;* (right) *gathering the metal;* (right rear) *blowing. Agricola, 1556.*

Flux, silica, fritting, and founding. It is clear that by 1450 glass-making in Venice was already highly developed, specialized, and organized on a large scale. Curiously enough, however, the first eye-witness account of Italian glass-making at this period describes processes seen apparently in Rome. This account is the *Glaskonst* ('Art of Glass') written by a Swedish priest, Peder Månsson, who travelled to Rome in 1508 and stayed there until he was recalled to Sweden in 1524. Månsson at the very beginning of his discourse puts his finger on the differences between Italian and northern glass-making:

> The art is practised in many lands and with different materials, and glass is not of the same type in all countries. In Rome and Welshland [Italy] glass is made of three sorts of materials: fine white sand, black ashes, made by burning a plant which is there called kali or alkali and in Italian soda, and of a salt which is called sal alkali, the ashes of which are imported from Spain and from Alexandria and France to Rome for the glass-making, and likewise from other countries. The soda-plant only grows on the sea-shore.

He then describes how the soda-plant is burned in a clay-lined pit, water poured on, more plant added, and the process repeated until the pit is full. On top is the black ash in lumps: underneath is the salt called sal alkali, agglomerated into a greyish stone-like mass. The sal alkali is cleansed by being powdered, sifted, and purified by lixiviation. Then equal quantities of fine white sand and of the black ash are mixed on the platform of a low-vaulted furnace fired with dry wood (cf figure 141). They are submitted to the fire for four or five hours, being constantly turned with an iron rake. When cool, the mixture is taken out, pounded, and sifted. This prepared frit is then ready to be put into the pots in the main furnace, where, after two days' intense firing, it is ladled with a long iron scoop from the founding-pot into the working-pot. The glass can be coloured by the introduction of suitable pigmenting substances, or rendered clear and white by the addition of 'manganese' [dioxide].

It will be observed that Månsson does not state how, or whether, his sal alkali was added to the batch. His account is in this respect supplemented by Vanoccio Biringuccio. In his *Pirotechnia* (Venice, 1540) Biringuccio states that the glass-salt ('sal vetro', Månsson's 'sal alkali') is taken and fritted with sand or powdered white river-pebbles in the ratio of one to two, and with a certain quantity of manganese [dioxide], in a reverberatory furnace. Biringuccio is also more explicit about the making of the glass-pots. He says that they are fashioned on the wheel from the refractory clays of Valencia, Treguanda, or elsewhere. The pots are dried in the shade for six or eight months, and are then placed in the fritting-furnace, the temperature being gradually raised until the pots become red in colour. Meanwhile, the wall of one arch of the main furnace (below, p 213) has been opened to allow enough space for a pot to be passed through, and the furnace fired to a red-heat. The pot is then hastily moved with iron tongs to the siege of the main furnace, and placed opposite one of the working-holes. The furnace described by both Månsson and Biringuccio is essentially that of Agricola's account, which, being illustrated and more complete, has been selected for discussion later (p 212). Månsson, however, gives an account of the actual

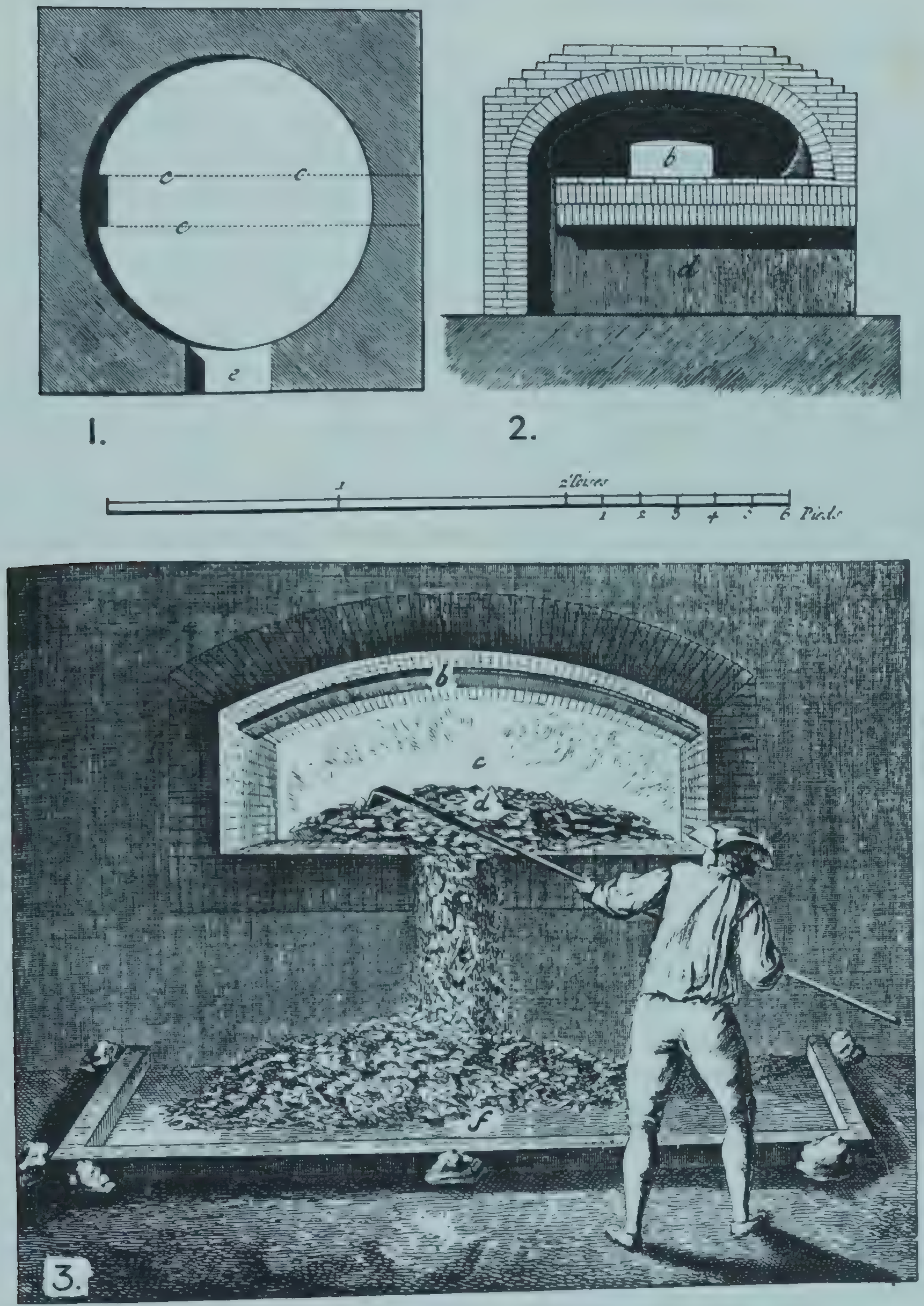

FIGURE 141—*The calcar (Fr.* carcaise) *or fritting-furnace.* (1) *Plan showing the line of the stoke-hole* (c–c) *and fritting-hearth* (e); (2) *transverse section showing the mouth of the furnace* (b) *and the flue* (d) *leading to the fritting-hearth;* (3) *general view showing furnace-mouth* (b, c), *frit on the hearth* (d), *and finished* (f) *ready for mixing with cullet for the founding. 1772.*

working of the glass which is more explicit than that of either of the others (cf figure 147):

First one wants an iron fifty-six inches long, nearly round or octagonal . . ., as thick as a thumb, and perforated with a hole no larger than a goosefeather. Dip this iron into a pot of molten metal and give it a twist, and forthwith the metal clings to the iron. Now you must be brisk . . . with your hands. Turn the iron round, smooth the metal on the stone in front of the furnace, make it fast on the iron and blow into it. Hold the glass again in the furnace, and turn the iron evenly in the flame. Take the glass out again and shape it with pincers to the form which it is finally to have. Swing the iron with the glass on it round in the air so that the glass may expand in length, and also expand it in breadth, like an ox-bladder, by blowing with the breath. Press in the end of the bulb with a point . . . or mould, and so make the base on which the glass is to stand; and with the pincers make it uniformly smooth all round. They now take a piece of wood two inches [fingers] broad, that is fastened from the upper part of the right thigh down to the knee. Next they moisten the iron pincers with a little spittle, and press them against the outer end of the glass where it is fixed to the iron, and place it in front of the opening to break it off. It breaks off at once where the spittle has touched it. The workman has also a second iron 56 in . . . long, shaped like the first, but not hollowed inside, called the Puntellum (puntee). This has always a piece of glass on its end and lies in the fire. With this iron fix the knob of glass on the base: it becomes attached at once, and is held in the oven to warm up. Then take it out and shape it with the pincers while rolling it on the wood bound on the thigh. . . . Then lay the finished glass in the other chamber to cool off, so that it does not get cold too quickly and break. Further, they have shears to cut the glass even, where necessary; and a variety of copper moulds, ornamented inside, or with rims. . . . Into these moulds they first blow the glass, and then take it out and blow it out wider. . . .

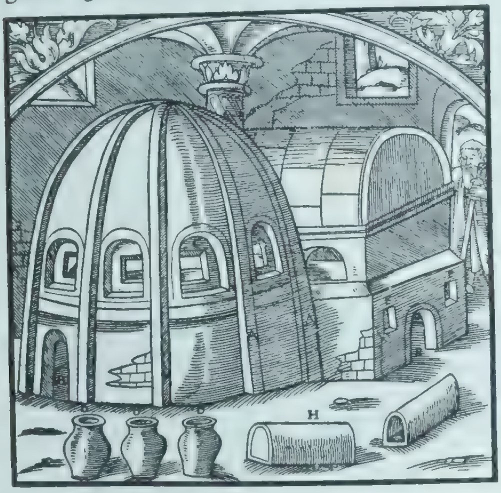

FIGURE 142—*The second furnace without the annealing-chamber but with conjoined annealing-furnace. Note the clay tunnels to contain the glasses to be annealed* (H). *1556.*

Furnaces. Agricola's account, although apparently to some extent based on Biringuccio's, is far ampler. He writes:

Some glass-men have three furnaces, others two, others one. Those who use three, cook the material in the first, re-cook it in the second, and in the third cool off the glass vases and other hot articles. Their *first furnace* should be arched over and resemble an oven. In its upper compartment, six feet long, four broad, and two high, the frit is cooked over a strong fire of dry logs until it melts and turns into a glassy mass. . . .

The *second furnace* is round, ten feet broad and eight high, and strengthened on the outside with five ribs . . . 1½ ft thick. This again consists of two chambers, the roof of the lower being 1½ ft thick. This lower chamber has in front a narrow opening for stoking the logs on the ground-level hearth; and in the middle of its roof is a big round aperture opening into the upper compartment so that the flames may penetrate into it. But in the wall of the upper chamber between the ribs there should be eight windows so large that through them the bellied [globular] pots may be put on the floor round the big aperture. . . . At the back of the furnace is a square opening, in height and breadth 1 palm, through which the heat may penetrate into the *third furnace* adjoining. This is oblong, eight feet by six broad, similarly consisting of two chambers, of which the lower has an opening in front for stoking the hearth. On either side of the stoke hole in the wall is a chamber for an oblong pottery tunnel . . . about four feet long, two feet high, and 1½ feet broad. The higher compartment should have two openings, one on either side, high and broad enough to admit the tunnels . . . in which the glass articles now made may be placed to cool off in a milder heat. . . . (figure 142).

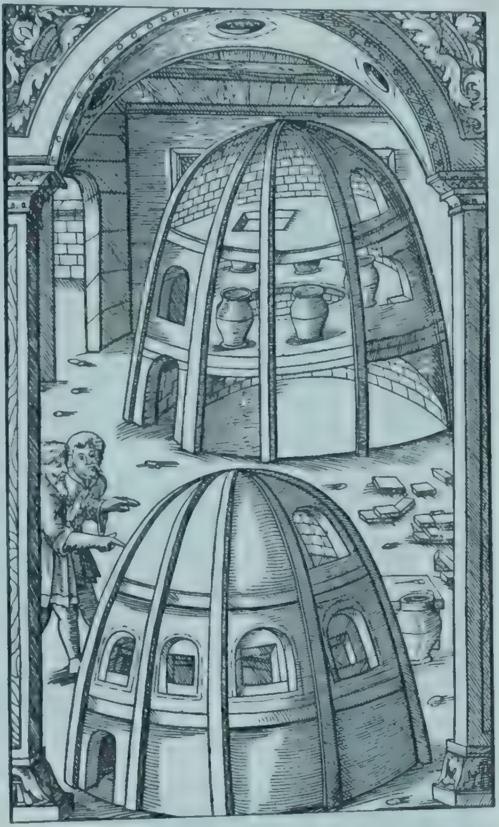

FIGURE 143—*Agricola's second glass-furnace, with annealing-chamber; a partially sectioned view showing the glass-pots within. 1556.*

Agricola goes on to explain that some dispense with the fritting-furnace, others with the annealing-furnace. In such cases the main furnace was of slightly different construction (figure 143):

But the second furnace of this type differs from the other second furnace, for it is round, but its open part is eight feet wide and twelve high, because it is composed of three chambers, the lowest of which is not dissimilar from the lower of the other second furnace. In the wall of the middle chamber are six arched openings which, when the heated pots are put in, are blocked up with clay, only small openings being left. In the centre of the roof of the middle chamber is a square opening, a palm long and broad, through which the heat penetrates into the topmost compartment. At the back of the compartment is an opening, so that into the oblong pottery tunnel placed in it the glass articles may be introduced to cool off gradually. . . .

It is clear from this account that a considerable variety of practice obtained in the writer's day. The general type of round furnace described by Agricola, however, remained in use for centuries (figures 144, 145, 423, 424).

Glasses and decorative techniques. To Månsson's account of the techniques in use when he visited the glass-house in Rome, Biringuccio's book adds one or two points. Thus: 'In addition to colouring [glass vessels] all possible tints, they also make them very clear and transparent like true and natural crystal, and ornament them with paintings and other very fine enamels. . . .' By the date of his book enamel-painting was going out of vogue, except perhaps for the German market, but he clearly refers to another ornamental technique which was at the time reaching the height of its technical accomplishment—the use of drawn-out opaque-white threads (*latticini*). He writes:

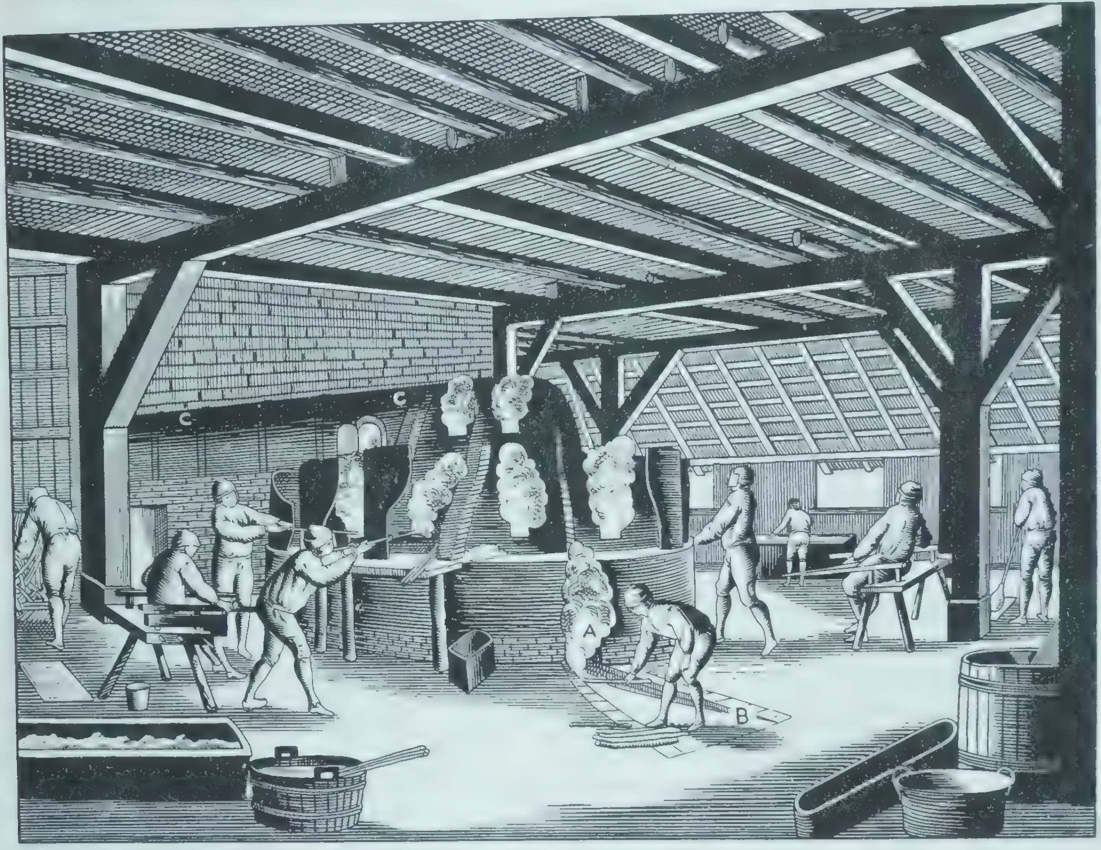

FIGURE 144—*Interior of a French glass-house making vessel-glass. Note the stoke-hole* (A, B), *and the long annealing-arch* (C) *along which the vessels were moved in 'fraches'* (*Fr.* ferraces = *iron trays*) *to the 'sarosel room'. 1772.*

> Look too at the large things as well as the small, that they make of white or coloured glass and that seem to be woven of osier twigs equally spaced. . . . I must tell you that I

have seen glass the colour of pearl or tinted green or blue or formed in various spirals made entirely of a single very slender fibre like a thread, more than 30 *braccia* long, all in one piece like gold or silver drawn through the draw-plate.

To the picture presented by the texts must be added the evidence of surviving glasses. In these the *cristallo* material is seldom completely colourless, having usually a brownish or greyish tint, due presumably to impurities in the materials. Of the coloured transparent glasses, emerald-green, blue, and manganese-purple are all found. No analyses appear to have been made of any of these glasses, and in the absence of such evidence we may at least provisionally assume that they were made by the processes described in the next section (p 218). Enamelling and gilding are both mentioned in the texts, but curiously enough not in conjunction as they are most often found in fact. The gilding was applied before the enamels, which overlay it. None of the sources mention the muffle in which such glasses were refired. Possibly the hottest part of the annealing-chamber or

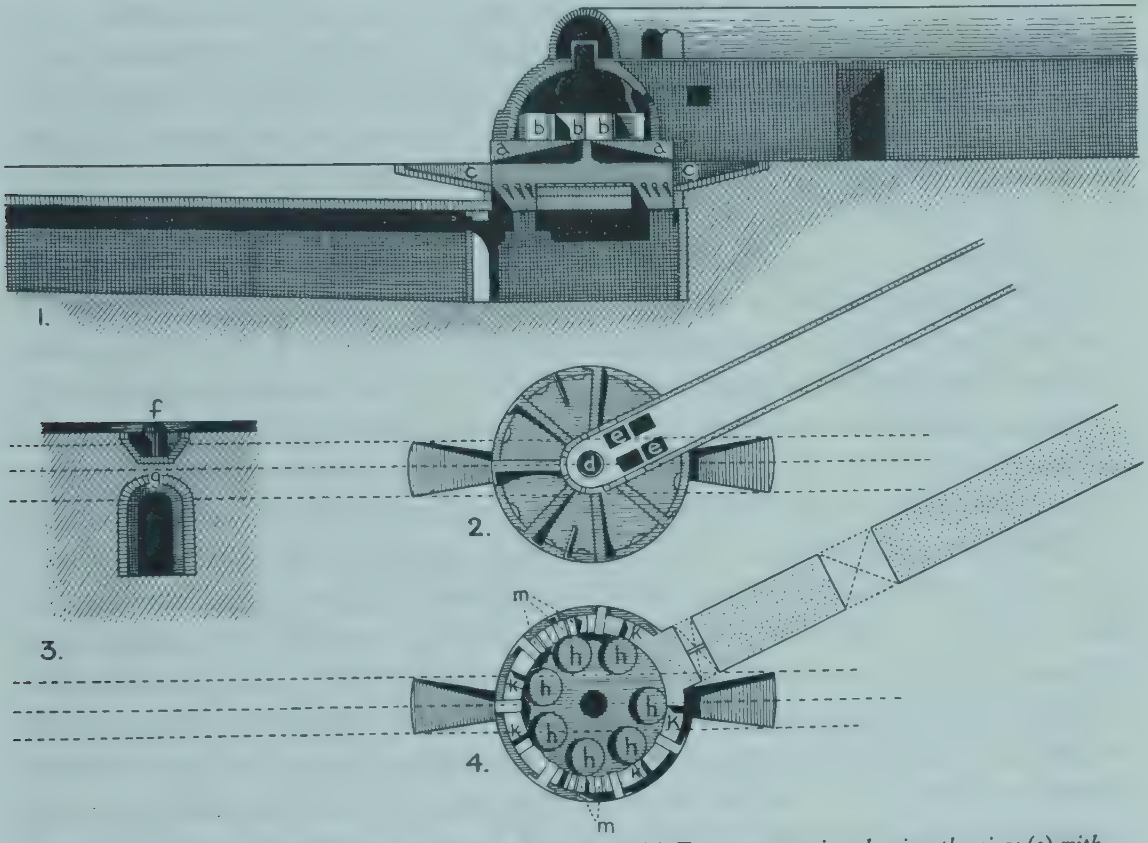

FIGURE 145—*Plan of the glass-house shown in figure 144.* (1) *Transverse section showing the siege* (a) *with pots* (b) *and stoke-hole* (c); (2) *plan at level of the annealing-arch showing* (d), *the hole communicating with the arch, and* (e) *fraches;* (3) *transverse section showing stoke-hole* (f) *and entrance to ash-pit* (g); (4) *plan at level of the siege, showing pots* (h, h), *working-holes* (k, k) *and boccarellas* (m, m).

the 'calcar' was used for the purpose, the clay containers shown in Agricola's wood-cuts (figure 142) serving perhaps to shield the glasses from fumes. Opaque-white glass was obtained by the use of tin oxide, and this too was occasionally made into hollow wares.

A further kind of opaque glass was that streaked with a variety of colours, mostly brown and greenish tones, in imitation of natural variegated stones (*calcedonio*, sometimes miscalled *Schmelz* glass). Enamel glasses were also made in many colours for use by goldsmiths, or, in tube form, as the raw materials of the *suppialume* (lamp) workers. In cane-form, both white and coloured, it was used for the *latticinio* decoration, rods of enamel glass being ranged round the inside of a hollow mould, picked up on a paraison of *cristallo* and marvered in. The ultimate complexity of this technique lay in blowing one paraison within another, the outer layer being decorated with canes wrythen in one direction, the inner with canes twisted in the other. The result was a reticulate pattern, often with an air-bubble trapped in each mesh (*vetro di trina*, lace-glass).

These cane-techniques were no doubt a by-product of the Venetian manufacture of tube- and rod-glass for the bead industry. Another technique was equally indebted to the Venetians' skill in cane-work. By this was made the *millefiori* glass, no doubt directly inspired by antique models, in which composite rods were built up in such a way as to form a pattern in the cross-section. Slices from such rods were probably then laid on a fire-proof tray, heated until soft, and then edged progressively together, finally forming a continuous sheet.

One further decorative technique should be mentioned—the making of the so-called ice-glass, with its crackled and fissured surface, whether by dipping the hot paraison in cold water, then reheating and reworking it, or by spreading broken glass on the marver, rolling the paraison on it, and incorporating the fragments.

Venetian metal, being particularly ductile, was usually worked thin. It was therefore not suitable for engraving by the glyptic technique of the lapidary. From about the middle of the sixteenth century, however, it was occasionally engraved by means of a diamond-point, which leaves a whitish spidery line on the surface of the glass. This linear technique was particularly taken up and developed at Hall in the Tyrol, in England, and in the Netherlands.

III. THE DISSEMINATION OF ITALIAN METHODS (*c* 1550–1615)

The great superiority of Italian glass-making rendered it the envy of all Europe, and princes and potentates everywhere sought to put themselves in control of glass-furnaces working in the Italian manner. Although heavy penalties were imposed on glass-workers absconding from Murano, the rewards were nevertheless sufficiently tempting to seduce many of them. There was, furthermore, a second source of supply of Italian glass-workers. This was the little town of, Altare, near Genoa, where the corporation of glass-makers followed a deliberate policy of disseminating its men and methods. Through the agency of workmen from these two sources, the Italian art of glass was spread throughout Europe, reaching even such distant parts as Sweden (in the 1550s), Denmark (by 1572), and England (by 1570 at latest). Unfortunately, apart from surviving glasses themselves, there is very little evidence as to the methods of glass-making used during this period of intense activity.

There is, however, a wall-painting in the *studiolo* of Francesco I de' Medici (Grand Duke of Tuscany 1574–87) which shows a glass-furnace of Venetian type at work (plate 30). It is clear that at this furnace the finished glasses were annealed in the top compartment of the founding-furnace. The glass-workers or gaffers worked seated, but had not as yet anything but their thighs on which to roll their irons. Particularly to be noted are the shields protecting the workmen, with the crooks (*halsinelle*) in which to rest the irons; the small 'glory-hole' (boccarella) in which the irons keep hot; the pucellas[1] with which the gaffer to the left is fashioning his glass; the shears (*tagliente*) and second pair of pucellas hanging at the right-hand side of his stool, in the time-honoured position; the boy between the gaffers engaged at a mould, and the 'servitor' on the right in the act of blowing; at his feet is the stoke-hole of the furnace: on the right-hand side is apparently a calcar corresponding fairly closely to that described by Agricola.

Little further light on glass-making is forthcoming until 1612, when there appeared Antonio Neri's *L'Arte vetraria*, the first and most famous textbook of glass-making. The greater part of the book is devoted to the coloration of glass, both to imitate gemstones and for the use of enamellers.

Fluxes. Neri opens with several chapters on the preparation of crystal-glass. His principal ingredients are '*Polverine*, or *Rochetta*, which comes from the *Levant* and *Syria* . . . there is no doubt that it makes a far whiter salt than *Barillia* of *Spain*'. The ashes are to be powdered and sifted, and then boiled in coppers until all the salts are extracted from the ashes. The lye is decanted into pans and allowed to stand until all sediment has been eliminated, and the salt-impregnated water is then heated until the salts begin to crystallize, when they may be removed with a skimmer for drying out. Before boiling the polverine, it was necessary to add to each copper about 12 lb of tartar of red wine, obtained as a deposit from wine-casks. The purpose of this was, no doubt, by the introduction of calcium,[1] to produce a more stable glass than would otherwise have been yielded by this highly purified soda. In subsequent chapters, Neri also refers to salt of fern-ashes, and salt from the ashes of bean-stalks, brambles, and other plants.

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[1] Or procellos, It. *borsello*, special flat-jawed tongs used in shaping glass vessels.

Silica. Neri mentions a moderate variety of sources of silica, of which tarso is the most important—'the whitest *Tarso*, which hath not black veins, nor yellowish-like rust in it. At *Moran* [Murano] they use the pebbles from Tessino. . . . *Tarso* there is a kind of hard, and most white marble, found in *Tuscany*. . . . Note that those stones which strike fire with a steel are fit to vitrifie . . . and those which strike not fire with a steel, will never vitrifie. . . .' This indicates that the tarso pebbles, although appearing to be marble, must have had a siliceous content; they were probably composed of calcium silicate. Tarso of the latter composition would have the advantage of introducing a further stabilizing dose of calcium into the batch. Neri also mentions, however, Tuscan sand from the valley of the Arno, natural crystal, firestones (presumably flints), and 'calcidonies'.

Fritting and founding. For fritting, the tarso had to be pounded small and sifted, then mixed with the prepared 'salt' in the ratio of 200: 130, and placed in the well-heated calcar. The mixture should be heated with a strong fire for 5 hours, being continuously stirred with a long iron rake. When the frits are put in the main furnace, 'then cast in such a quantity of *manganese* prepared as is needful. . . '. Here, as elsewhere, everything is subject to the experience of the furnace-man (*conciatore*).

Colours. The main emphasis of Neri's book is on the colouring of glass. It is impossible here to go into the details of his recipes and processes, but it may be said in general that his blues are based on cobalt, his purple tones on manganese, red on iron and copper, yellow on iron, and green on copper, the metals being introduced mainly as oxides. Variations of tone were achieved by using mixtures of the metallic oxides.

Concerning cobalt, Neri merely provides instructions for its preparation by calcination, trituration, and precipitation; Merrett (1662) knows that it comes from Germany, and says that in England it needs no more than grinding before use. Kunckel (1679), however, is fully aware of its character and preparation, and specifies Schneeberg, near Meissen, as one of the sources of supply. Of manganese, Neri recommends that of Piedmont as the best, that of Tuscany and of Liguria containing admixtures of iron and thus causing a blackish tinge; Merrett adds that good manganese was obtained in his day as a by-product of the lead-mines on Mendip. Copper is used in the form of calcined brass, called *ferretto di Spagna* (*aes ustum*), of verdigris, or of various products made by calcination or by solution in acids, and so on. Iron, similarly, was used in the form of *crocus martis* (ferric oxide) produced by calcination or precipitation.

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[1] Tartar of wine consists mainly of potassium hydrogen tartrate but contains a certain amount of the calcium salt as well.

Calcedonio. Apart from his recipes for clear colours, Neri gives instructions for founding a variety of different glasses. Thus in chapters xlii–xliv he gives three recipes for making *calcedonio* glass (with veining resembling agate and other natural stones) which mainly involve dissolving in *aqua fortis* (nitric acid) the various metallic substances already mentioned, mixing these solutions, and obtaining a powder by precipitation from the mixture; this powder is then added to the batch with an admixture of calcined tartar, chimney-soot, and *crocus martis*.

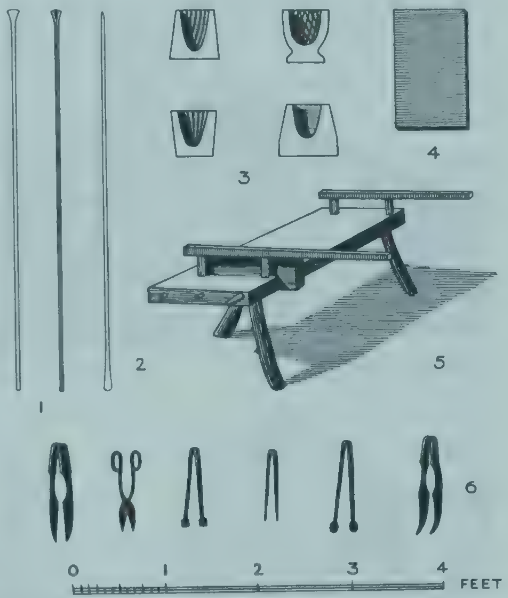

FIGURE 146—*Glassworker's chair and tools.* (1) *Blowing-iron;* (2) *pontil;* (3) *moulds;* (4) *cast-iron marver;* (5) *chair;* (6) *pucellas and shears. 1772.*

Glass of lead. Neri's fourth book is wholly given over to the making of 'glass of lead' or lead-glass, the high refractive index of which admirably suited it for use in counterfeiting precious stones. Neri's precepts, and the observations on them made by Christopher Merrett (1614–95) in his English version of Neri's book (1662), may well have proved highly suggestive to George Ravenscroft in his experiments later in the century (p 221).

Enamel glass. Lastly, in chapter liv, and thereafter in his sixth book, Neri deals with the making of enamel—that is, opaque glasses of different colours. The opacifier is in every case calcined tin, although Merrett, in his commentary on chapters xvi–xix, advocates the use of antimony and saltpetre ground together and mixed with the materials for crystal glass.

IV. DEVELOPMENTS IN THE SEVENTEENTH CENTURY

The glass-maker's 'chair'. Although Neri's remained the standard textbook for the technological aspects of glass-making throughout the seventeenth century, it throws no light on glass-house practice. This is particularly unfortunate in that the period between about 1575 and 1662 saw the evolution of one of the basic appliances of glass-making by hand. This was the gaffer's 'chair' (figure 146), on which he trundles blowing-iron or pontil to preserve the circularity of the vessel as he works (figures 144, 147). This was no doubt a development of the long piece of wood bound to the thigh, as described by Månsson at Rome (p 212), but one can do no more than speculate as to where it was invented. The first written mention of it appears to be in Merrett: 'They sit in wooden large and wide Chairs with two long Elbows.' It seems probable that the chair was evolved by the Italian-manned glass-making centres in the Netherlands. Apart from this innovation, which was probably adopted rapidly all over Europe, the main developments in European glass-making in the seventeenth century took place in England and in the German-Bohemian area.

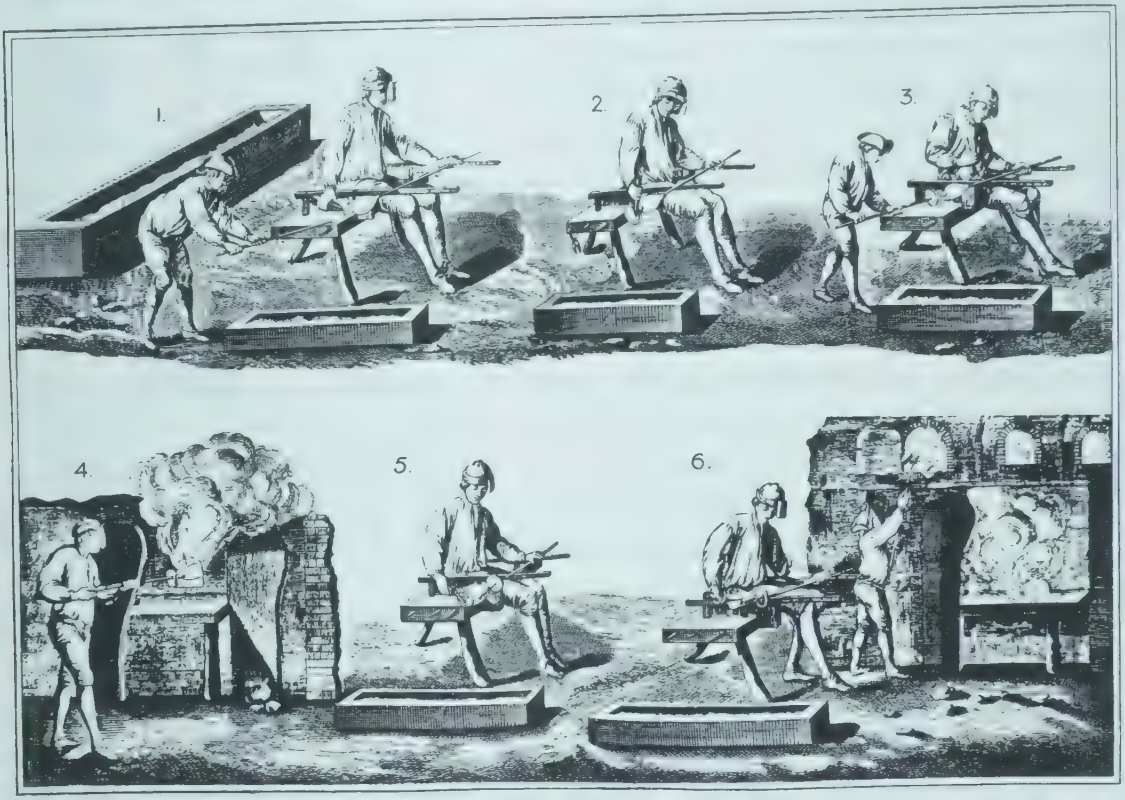

FIGURE 147—*Stages in making a wine-glass.* (1–2) *Shaping the foot;* (3) *attaching pontil and knocking off paraison;* (4) *warming-in;* (5) *trimming the rim;* (6) *shaping the bowl and putting the finished glass to anneal. 1772.*

England: coal-burning. The history of glass-making in England was radically transformed in 1615 by a 'Proclamation touching Glasses' which forbade the use of wood for firing glass-furnaces (p 78). This development had already been foreshadowed both by increasing public concern about the rapidly diminishing national resources of timber, and by the successful application of coal-firing to a number of other industrial processes (ch 3). There is no contemporary description of the English coal-burning furnace of the seventeenth century, but some idea of it can be formed from Merrett's commentary on Neri, and from a remarkable set of drawings made by a Swedish architect visiting London in 1777–8 (figures 148–9). The essential difference between it and the old wood-fired furnace appears to have been that (in the case of the rectangular 'green' glass-furnace) the coal was fired on a grille of iron bars laid longitudinally and supported on a number of shorter cross-bars (figures 149 c, 152 b). Beneath this grille was an ash-pit which could be entered for clearing. Firing with coal seems to have yielded higher temperatures than the older method, and the 'green' glass-furnaces in particular, which Merrett deemed to develop the greatest heat of any then known, had to be built with special materials.

The use of coal seems, in the course of the century, to have prompted the invention of a covered pot of the modern type, with a tubular outlet to the working-hole. It seems clear, however, that such pots were used only in the houses working clear glass, for the bottle-houses illustrated in figures 148–9 and 151–2 used the old open pot. Merrett in 1662 makes no mention of covered pots, and although it has often been assumed that they were part and parcel of the coal-firing process, and therefore introduced early in the seventeenth century, there is no real evidence for this assumption. The compounds of sulphur produced by the combustion of coal, however, would react with any lead in a batch to produce lead sulphide, which is black in colour. To obviate this discoloration, a covered pot might well have suggested itself, and this development may therefore be intimately connected with the epoch-making invention that follows.

The invention of lead crystal. George Ravenscroft is, by common consent, accepted as the inventor of lead crystal. Starting in 1673, he first produced a 'sort of crystalline glass resembling rock crystal'. This, however, had the grave disadvantage of developing gleaming hair-like fissures ('crizzeling' or 'crizzling'), caused probably by an excess of salts. In 1675 Ravenscroft appears to have started to use lead oxide, thus reducing the ratio of salts and stabilizing the glass. By the end of the century the process had become common property amongst English glass-makers, and towards 1700 there was a growing tendency to put more and more lead into the batches, the result being a very heavy metal of a dark and 'oily' brilliance.

Germany and Bohemia: the invention of potash-lime crystal. The same movement that led in England to the production of lead-glass appears to have brought about simultaneously in Germany the evolution of another type of glass which was much closer than Venetian-type *cristallo* to true crystal in clarity and brilliance. This was a potash-glass made with an addition of chalk. The exact date of its introduction is uncertain, but a 'crystal-glass' mentioned in 1677 was probably already a potash-lime glass. Some glasses of this type probably owed their lime-content merely to the ash from which they were made, but Johann Kunckel (1630–1703), in his *Ars vitraria experimentalis* (1679), specifically refers to the addition of chalk. In the second edition of his book (1689) he gives a recipe consisting of 150 lb of sand, 100 lb of potash, 20 lb of chalk, and 5 oz of manganese. There were no doubt many other similar recipes current in the late seventeenth century. Being a solid and colourless glass, this 'crystal' was particularly suited to wheel-engraving, an art that constitutes the chief glory of German glass during the seventeenth and eighteenth centuries.

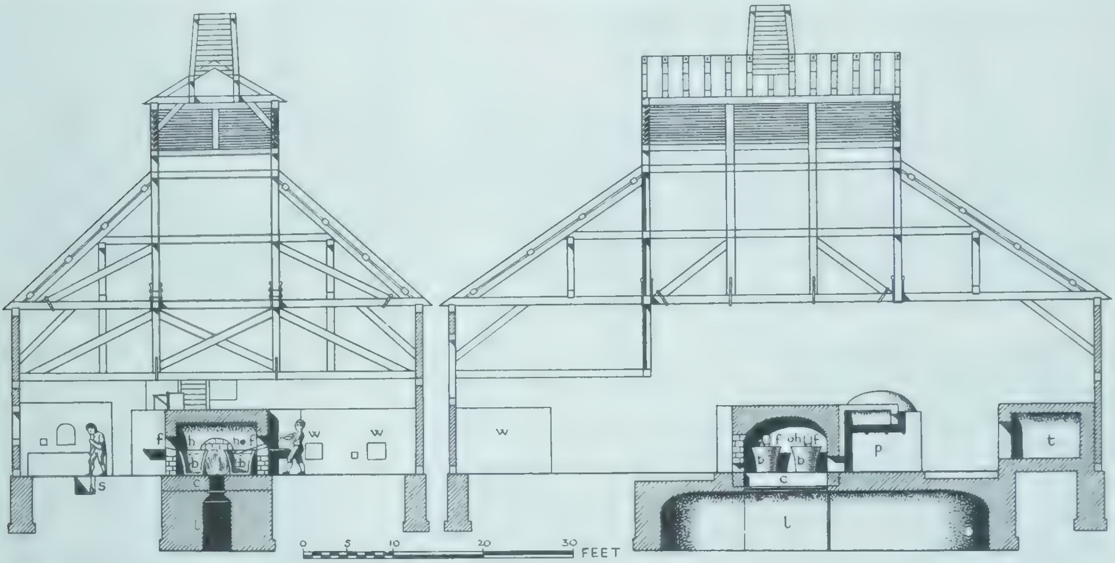

FIGURE 148—*View and plan (figure 149) of a London bottle-glass works, by C. W. Carlberg. 1777–8. The drawing gives sections along the lines* A–B *and* C–D *on the plan. The furnace was 9 ft square inside and 6 ft high. The pots* (b) *were 3 ft high, 3 ft 1½ inches in diameter above, and 2 ft 2 in below. Note also the grille for burning coals* (c), *working holes* (f), *boccarella* (h), *ash-chamber* (l), *fritting-furnace* (o), *furnace for heating cullet* (p), *linnet-holes* (q), *hole in ground for blowing bottles in moulds* (s), *furnace for pre-heating pots* (t), *annealing-ovens, each of the two largest taking 800 bottles* (u, w).

Wheel-engraving. It is generally agreed that glass-engraving was a by-product of hard-stone engraving, the process being merely transferred to the softer, artificial substance. When this transference originally occurred is not known, but it is almost certain that glass-engraving was being practised before the end of the sixteenth century. There is also uncertainty about the tools used for the work. Sandrart, who is the main source of our information concerning the earliest engravers, wrote in 1675:

Now although these artists had brought to perfection the art of glass-cutting as far as it depended upon judgment and drawing, yet in consequence of the too powerful and clumsy machinery made use of by them, even they were unable to give grace and charm to their work. When we consider the big heavy wheels that they were fain to employ—turned by those still flourishing weeds, their loutish assistants—we may well marvel at the work they turned out. Since that time the discovery of more convenient and efficient tools has brought it about that nowadays the art of glass-cutting is no longer a strenuous task, but rather a pastime. . . .

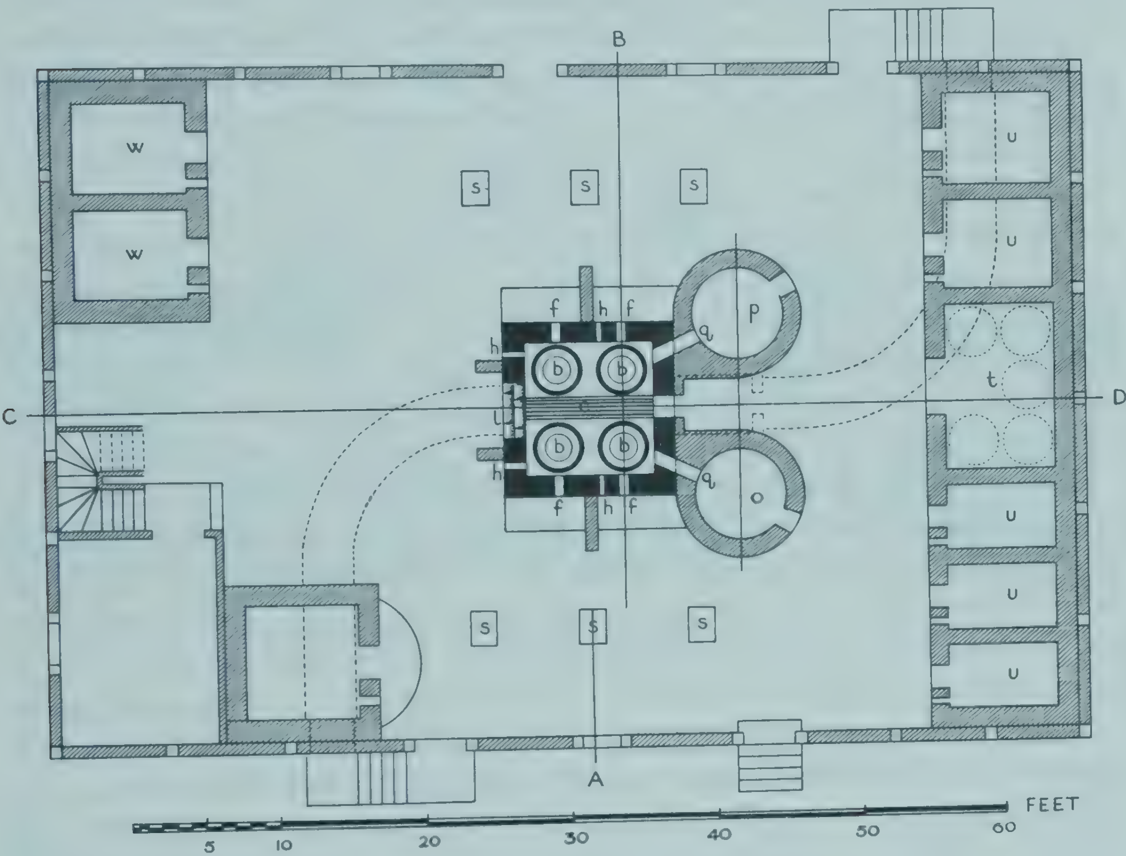

FIGURE 149—*Plan of the bottle-glass works shown in figure 148.*

It has been objected that the treadle-operated engraving-wheel was already known in the time of Jost Amman (1568); but the fact remains that in Prague, as late as 1653, the wheels used in the workshop of the Court hardstone engraver, Dionisio Miseroni, were still of the old type—the apprentices turning by hand huge fly-wheels, from which bands ran down to the spindles in which the engraving-wheels themselves were fixed. Later in the seventeenth century water-power was largely used, perhaps as a result of the contemporary demand for glasses carved in high relief (*Hochschnitt*), in which the whole unpatterned surface of the glass was ground down to a depth of some millimetres, at the cost of an enormous expenditure of effort. The date of the general introduction of the treadle-operated wheel for intaglio engraving (*Tiefschnitt*) is uncertain, but it is reasonable to assume that it was to this innovation that Sandrart referred. No early example of such an apparatus appears to have survived, but in the Stockholm city museum there is an early nineteenth-century specimen which is probably in all essentials of the traditional pattern. In this, a treadle-operated fly-wheel transmits power by means of a band to a spindle mounted horizontally above a working-bench. The end of this spindle is hollowed out to form a gently tapering hole. Into this can be fitted a series of steel spindles, each bearing a cutting-wheel. These wheels, usually of copper, are of varying profile and size, ranging from about 1 to 10 mm, and require to be changed frequently in accordance with the needs of the work. Above the wheel is fixed a strip of felt to feed it with the mixture of oil and abrasive which actually cuts into the glass, pressed against the wheel from below. It may be surmised from later practice that, after the design had been roughed out, wheels of lead and pewter, then of fruit-wood, would be used, in conjunction with progressively finer abrasives, to polish the work. It is not known for certain what abrasives were used in early engraving.

Opal and opaque-white glass. A second technological development taking place in the German glass-houses in the seventeenth century was the manufacture of glass made opalescent or opaque by the addition of calcined bone or horn. In the first edition of his book (1679) Kunckel speaks merely of the 'ashes of burned houses and barns', but points out that this opacifier is effective only after reheating the glass; in the second edition (1689), however, he gives two recipes that include burned bones or stag's horn. He observes that the degree of opacity is affected by the amount of warming-in to which the glass is subjected, as also by the proportion of ash in the batch. These glasses could be coloured at will.

Ruby-glass. That gold was already familiar as a glass pigment in the sixteenth century is suggested by a passage in Agricola's *De natura fossilium* (1546).[1] Neri too (1612) speaks of a wonderful red obtained from gold (book V, ch xc). No early glasses of this type are known, and the use of gold chloride did not come into its own until the last quarter of the seventeenth century, in Germany. This development also was due to Kunckel, but he expressed his indebtedness to

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[1] According to R. Campbell Thompson, the ancient Assyrians (seventh century B.C.) knew how to make ruby-glass by the use of gold. See his 'A Dictionary of Assyrian Chemistry and Geology', Oxford University Press, 1936, pp xxxi–xxxvi.

Andreas Cassius (1640?–?1673), of Hamburg. Cassius discovered that on adding tin chloride to a solution of gold chloride, a purple powder (purple of Cassius) is precipitated. When glass is fused with this powder and annealed, it takes on a fine ruby colour. The powder probably contains colloidal gold. Kunckel left no recipe for ruby-glass, but an eighteenth-century Potsdam formula no doubt reflects his practice. This prescribes taking a gold ducat beaten out thin and cut into pieces, and placing it in an alembic with ½ oz of nitric acid, 1½ oz of spirit of salt, and 1 dram of sal ammoniac. This mixture should be subjected to heat until the gold is dissolved, when the solution is incorporated in a crystal-glass batch.

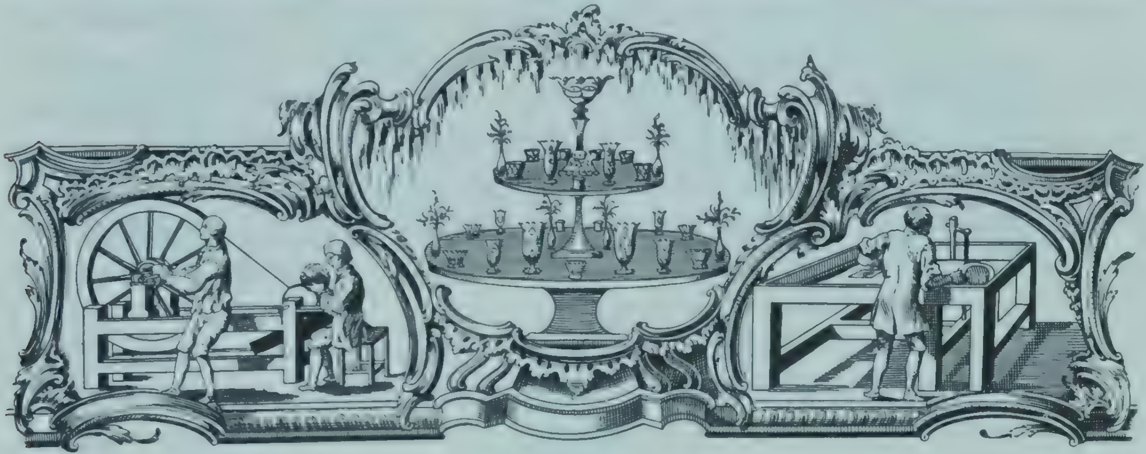

FIGURE 150—*Detail from a trade-card of the glass-dealers Maydwell and Windle, showing* (left) *a glass-cutter at work. c 1775.*

This process too required the developing action of reheating before the ruby colour achieved its full strength. The process was rapidly disseminated among the German glass-houses, and was possibly also known to Bernard Perrot at Orleans as early as 1668.

V. THE EIGHTEENTH CENTURY

England. The tendency to add more and more lead oxide to the batch was modified in the early decades of the eighteenth century, and was sharply checked in 1745–6 by an excise levied on glass by weight. English glass-men were thereafter driven to compensate for the reduced bulk and impoverished metal of their glass by adventitious ornament such as enamelling and gilding, which have already been mentioned in the section on Venetian glass, and by wheel-engraving (p 222).

Cutting. Lead-glass was uniquely suited to decoration by cutting, both because of its high refractive index and because of its relative softness in working.

Very little is known for certain about the equipment and materials used for glass-cutting in the eighteenth century. Inferring from later practice, it is probable that the first cuts were made with an iron wheel upon which sand and water fell from a hopper above. The rough cuts were probably then smoothed on a stone wheel running in a trough of water, and finally polished on a fruit-wood wheel fed with fine abrasives. What these were is not definitely known, but the stock of a glass-house at Dudley in 1784 included 'emery . . . pumice stone, &c.', apparently for cutting rather than for engraving. A contemporary illustration (figure 150) shows that the cutting-wheel, here probably of stone, was set in a frame and powered by a hand-turned fly-wheel like the earlier engraving-wheels (p 223). As is shown in the figure, the workman normally presses his glass down upon the wheel. This enables him to exert considerable pressure and to obtain a powerful cutting-action from the wheel, which turns towards him. Such a craftsman was called an overhand-cutter; underhand-cutters presumably worked on the opposite principle, using a wheel that turned away from them, and holding the glass underneath it, like the modern intaglio cutters. This probably permitted a finer type of work.

An examination of mid-eighteenth-century cut glasses suggests that the wheels used were of blunt profile, either flat, rounded, or with an obtuse bevel. With such wheels, over-all patterns of a simple character could be obtained by presenting the glass to the wheel in the axis of its rotation. A richer type of cutting was evolved in the third quarter of the century by combining these elements with cuts made by presenting the vessel obliquely to the cutting edge, thus producing asymmetrical, lunate forms.

The glass-cone. Until the late seventeenth century the glass-house was built up round the furnace like a barn, with a pitched roof, and usually a louvred lantern above the furnace (figure 148). At some time in the century the cone-shaped glass-house was introduced, permitting the concentration of all air-currents in a single upward movement. This structure appears to have given greater efficiency in the use of fuel, and it is singled out by the writer on glass in the great *Encyclopédie* (1751–76) as one of the prime advantages of the English glass-houses (figures 151, 152). A patent granted in 1734 to Humphrey Perrott, of Bristol, for 'A Furnace . . . [which] is contrived in a new Manner with Artificial Draughts to it, whereby to force the Heat or Fire the sooner to perform its office . . .' may be connected with this innovation.

Fluxes. R. Dossie, in 'The Handmaid to the Arts' (1758), states: 'The substances which are used as *fluxing* ingredients in glass, are red lead, pearl-ashes, nitre, sea salt, borax, arsenic, the *scoria* of forges, commonly called *clinkers*, and

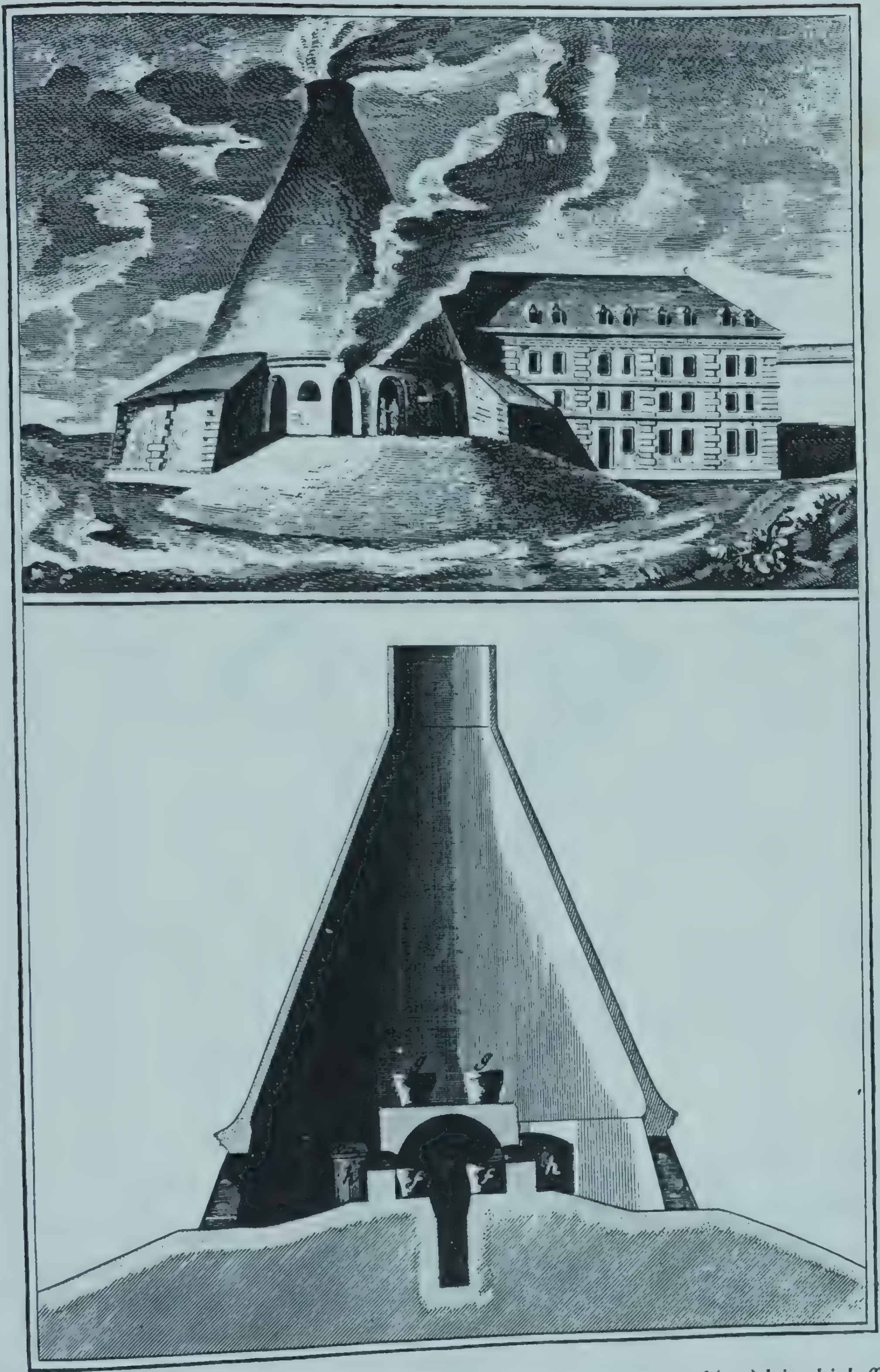

FIGURE 151—*The English type of glass-house cone. Note pots* (f, f) *on the siege and* (g, g) *being dried off; and the annealing-arches* (h, h). *1772.*

wood-ashes containing the calcined earth and lixiviate salts, as produced by incineration.' There is little new here except borax and clinkers. Borax was imported from the East Indies in the form of tincal,[1] and on account of its exorbitant price was used solely for looking-glasses. Clinkers, obtained from iron-foundries, were used only in bottle-houses, and served to reduce the quantity of wood-ash required. Their iron impurities would be no objection in making

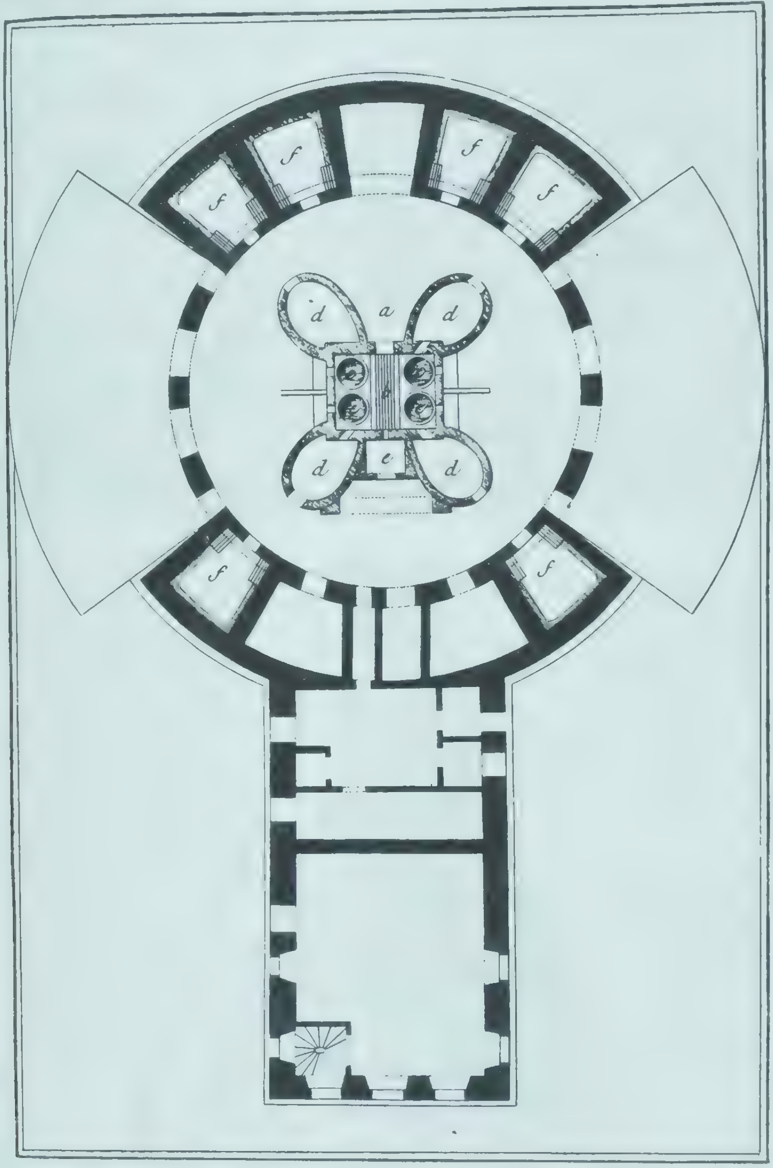

Figure 152—*Plan of the English-type glass-house shown in figure 151. Note the grille for burning coal* (b); *the pots* (c); *the pot-arches* (d); *the fritting-furnace* (e); *the annealing-furnaces* (f). *1772.*

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[1] Malay *tingkal*, Urdu *tinkar*, *tarkar*, crude borax.

dark wine-bottles. At this period, the potash used for the finer kinds of glass was imported in a refined form, known as pearl-ash, from Germany, Russia, and Poland; at a slightly later date it came also from America.

Opacifiers. To the substances prescribed by Neri and Kunckel may be added arsenic, mentioned by Dossie when discussing enamels. Arsenic produces its effects by crystallization during the cooling of the glass, and its effects may already have been familiar to Kunckel.

Transparent ruby lead-glass. On 5 December 1755 one Mayer Opnaim took out a patent for red transparent flint-glass. Opnaim was clearly of German descent, and his achievement lay in applying the German method of making ruby-glass to the English lead-fluxed material. The patent specification is too lengthy to be described here, but Opnaim's method involved the use of both pyrolusite (*Braunstein*) and dissolved Dutch gold.

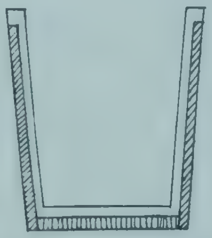

FIGURE 153 — *Section through* 'Zwischengoldglas' *showing outer shell* (diagonal hatching) *and separate base-disk* (vertical hatching)*: the etched gold-leaf was laid between these and the inner shell of the beaker* (unhatched).

Decorative innovations on the European continent. Although the Dutch poetess Anna Roemers Visscher (1584–1651) had used stipple-engraving in 1646 on one of her diamond-point engraved glasses, the technique was not fully exploited until in 1722 Frans Greenwood decorated several glasses in this way. One of the most prolific stipple-engravers was D. Wolff, of The Hague. This artist is stated to have stippled 'with the help of a small etching needle driven by a little hammer'. Hardened steel points can make impressions on soft glass, but this account is unsubstantiated and should perhaps not be taken at its face value.

'*Zwischengoldgläser*' (gold-sandwich glasses). During the second quarter of the eighteenth century, in the German-Bohemian area, a decorative technique was evolved by means of which gold-leaf (or silver, or both), etched with a point to the desired design, was sandwiched between the two thicknesses of a double-walled glass—usually a beaker (figure 153).

VI. LENSES AND OPTICAL INSTRUMENTS

Lenses and lens-grinding have played a fundamental part in the history of technology. During their evolution from simple magnifying and diminishing glasses to their use as spectacles, to their combinations in telescopes and microscopes, and to still more complex uses, lenses have transformed some sciences and virtually created others.

The magnifying power of glass spheres filled with water was known to the Greeks. Some of their optical properties were elucidated by Ptolemy in the second century A.D., in his 'Optics'. Islamic writers developed the optical conceptions of the Greeks; foremost among them was Ibn al-Haitham (Alhazen, *c* 965–*c* 1039) whose work has a sound experimental basis. He studied the reflective properties of curved mirrors, and the magnification of segments of glass spheres was well known to him. His study of the rainbow was translated into Latin about 1170, and his 'Optics' in 1269; these translations had a profound effect upon European philosophers.

Among the earliest western scholars to make original contributions to optical theory was Robert Grosseteste, bishop of Lincoln (*c* 1175–1253), who first drew attention to the practical usefulness of lenses in making small things appear large and distant objects near. Grosseteste also developed an important theory to explain the formation of the colours of the rainbow by refraction. His theory of the double refraction of light passing through a spherical lens or burning-glass—one refraction on entering the new medium and another on emerging from it bringing the rays to a focus at a point—was accepted until the sixteenth century. Roger Bacon (*c* 1214–94), a pupil of Grosseteste, followed Alhazen's more experimental trend. Conceiving of an instrument serving the purpose of the telescope, he explored the laws of refraction with the aid of plano-convex lenses, his aim being the practical one of improving vision.

Spectacles were already in use in northern Italy at the time of Bacon's death. A certain Friar Giordano of Pisa, in a sermon preached at Florence in 1306, said:

> It is not yet twenty years since there was found the art of making eye-glasses which make for good vision, one of the best arts and most necessary that the world has. So short a time is it since there was invented a new art that never existed [before]. I have seen the man who first invented and created it, and I have talked to him.

This is strong evidence that the invention was made about 1286, but the name of the inventor is unknown. Spectacles were almost certainly not invented at Venice, but they were soon being made at this principal centre of the glass-industry, which had developed in response to the need for window-glass and fine vessels. In 1300 the Venetian guild by-laws relating to *cristalerii* (glass-workers) mention *roidi* (for *rodoli*) *da ogli* (little disks for the eyes) and in 1301 *vitreos ab oculis ad legendum* (eye-glasses for reading). In 1316 'eyeglasses with a case' (*oculis de vitro cum capsula*) were sold for 6 Bolognese soldi. Thereafter references to spectacle-making accumulate rapidly (figure 154). The first portrait depicting spectacles was painted by Tommaso Barisino of Modena in 1352 (plate 1).

Though the Venetian glass-industry was making a product of sufficiently high quality for use in spectacles before 1300, it was much below the excellence afterwards achieved. At first spectacles were provided with convex lenses only, to aid presbyopia; the lenses were ground to curves of small radius, and were comparatively easy to work. No reference to concave lenses for the correction of myopia appears to precede that of Nicholas of Cusa (1401–64) in the mid-fifteenth century. The manner in which lenses correct the natural defects of the human eye began to be studied in geometrical terms in the sixteenth century. Francesco Maurolico (1494–1575) of Naples showed how the lens of the eye focused light upon the retina, and by 1600 Geronimo Fabrizio (1537–1619) had shown that the lens occurs in the front part of the eyeball rather than in the middle, where error had long placed it.

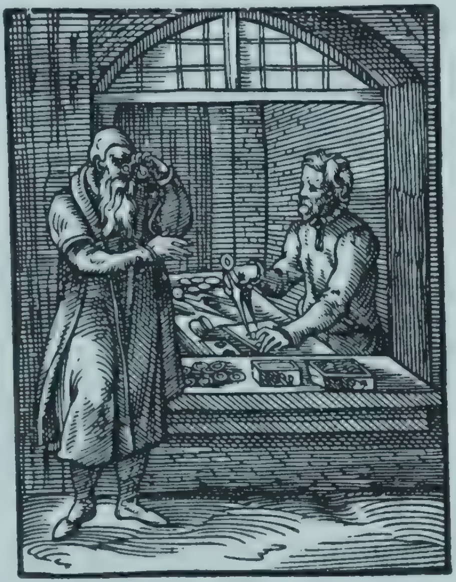

FIGURE 154—*Spectacle-maker's shop, 1568. Note the dividers for marking out the glass, and (on the bench) the little handle for manipulating the lenses during grinding.*

There are references as early as the mid-sixteenth century to reputedly successful attempts to devise optical instruments whereby distant objects could be seen more plainly, and enlarged. The English mathematicians Leonard Digges (1510–58) and John Dee (1527–1608) both made experiments to this end. Usually, however, it has been thought that the first practical telescopes were the result of fortuitous observations by a Dutch spectacle-maker about 1608, who hit upon the combination of a convex objective with a concave eye-lens giving an erect image. Certainly at this time the Dutch first made such instruments, which attracted attention and were put to military uses. But according to a reliable record of 1634 Johannes Janssen or Jansen, the son of the fortunate spectacle-maker, declared that his father 'made the first telescope amongst us in 1604, after the model of an Italian one, on which was written *anno* 1590'. Thus the Dutch telescope appears after all to be derived from Italy, the main centre for glass-working and optical study. Moreover, this record gives further significance to the description by Giambattista della Porta of Naples (1536–1605), in the second edition of his *Magiae naturalis* (1589), of ways to improve vision at a distance, including the combination of a convex and concave lens. His account is deliberately obscure. What is puzzling is that Galileo (1564–1642) should have known nothing of this, until he learned in 1609 of the Dutch 'invention'. Galileo was the effective scientific inventor of both the telescope and the compound microscope. His first instrument was a lead tube 2·9 m long and 42 mm in diameter, carrying a plano-convex objective and a plano-concave eye-lens with a magnification of three diameters.

Credit for the invention of the compound microscope has been variously assigned. della Porta again seems to have constructed a compound microscope, but the history of the instrument effectively begins with Galileo's use of what was actually a Galilean telescope with a very short working-distance to discern the organs of small creatures. By 1612 (according to Viviani) Galileo had presented such microscopes to various persons. Their tubes were necessarily very long, to permit the short working distance. The combination of two convex lenses (giving an inverted image) was a great advance on the Galilean lens-system, for both telescopes and microscopes; it was first described, as a telescopic arrangement, by Kepler in 1610. In the latter part of the century all scientific optical instruments employed the Keplerian combination of lenses, which was further improved by other workers (figure 371).

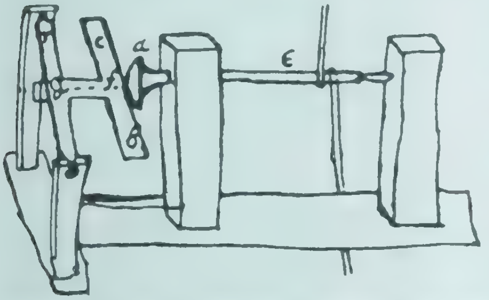

FIGURE 155—*One of Newton's proposed machines for grinding hyperbolical lenses. 'y^e glasse* a *may be ground Hyperbolicall by y^e line* cb, *if it turns on y^e Mandrill* ε *whilst* cb *turns on y^e axis* rd *being inclined to it as was showed before.'* c *1666.*

As experimenters strove after higher magnifications, the defects of existing lenses and their combinations were revealed more sharply. These were of three kinds. First, there were faults of craftsmanship: the glass was not free from flaws, or was poorly figured and polished. Secondly, it is inherently impossible for a spherical lens (or mirror) to bring the light incident upon it to a point-focus, and this spherical aberration causes lack of definition in the image. Thirdly, at more than mediocre powers and apertures the image is surrounded by coloured fringes due to the chromatic aberration of the lens, and these cause further confusion. The first of these defects could be overcome; some scientists—like Huygens and Leeuwenhoek—ground their own lenses with consummate skill. The remedy for the second was revealed by Descartes in 1637; the lenses and mirrors must be given a parabolic or hyperbolic curvature, which renders them capable of reflecting or refracting the light to a point. Descartes suggested various impracticable ways of doing this, and the mechanical problem was further explored by Newton (figure 155), but a solution was impossible. In practice lenses had to be ground as portions of spheres. For telescopes, spherical aberration could be mitigated by making the focal-length of the objective very great in proportion to its diameter: 48 ft was not uncommon, and tubeless telescopes 200 ft long were tried. Microscopes were improved by using three- or four-lens systems, stopping down, and renouncing very high powers (figures 370, 372, and tailpiece).

The cause of chromatic aberration was made plain by Newton's investigation, published in 1671, of the prismatic colours. He showed that a lens does not refract light of different colours to the same point; therefore a lens, however figured, cannot form a single image save in monochromatic light. Since white light is compound, it forms a series of coloured images. Newton, thinking that this dispersion of the colours was in a fixed ratio to the refraction, regarded chromatic aberration as incapable of remedy; hence after he had made these discoveries he turned to the reflecting telescope (figure 369). In fact, by combining convex and concave lenses of suitable refractive indices, a composite lens can be made which refracts white light without widely dispersing it, and is therefore practically achromatic. This was first discovered empirically by Chester Moor Hall in 1733, and rediscovered by John Dollond in 1758, who put his success to commercial use. The achromatic microscope was not manufactured commercially for another seventy years, again preceded by various ingenious reflecting instruments.

Thus, by about 1680 the development of instruments using lenses came to a halt from the optical point of view, though their mechanical properties were greatly improved and elaborated (p 633). Neither the refracting telescope nor the microscope was capable of extending its range of vision. In the eighteenth century astronomers turned increasingly to the reflecting telescope for qualitative work (it was brought to a high pitch of perfection by James Short and the elder Herschel, who made a 48-in mirror). Biologists mostly employed the simple microscope, which was easy to manipulate and reliable, but low-powered. None emulated the genius of Leeuwenhoek, who made and worked with single lenses having a focal length of 0·05 in, or even less (figure 368).

VII. GRINDING AND POLISHING LENSES

Natural stones and glass have been cut, ground, and polished from early times, the diamond being used for cutting and sand or emery for abrasion. Lens-grinding involved no new principle, save that it was directed towards the production of a glass accurately curved, or perfectly plane, and polished free from scratches. Two aspects of the technique merit special attention: (i) the nature of the material to be worked, and (ii) the character of the apparatus to be used.

Composition of the glass. It is very remarkable that though the scientific investigation of glass and glass-making is very recent, the composition of the batch still standard for modern bottle- and window-glass is practically identical with that used by the Venetians for their glass in the Middle Ages, having remained unchanged throughout the centuries. The explanation would seem to be that while research has revealed the basis for the ancient empirical formula, it has not been able to improve upon proportions which long experience and trial-and-error proved to be the best for their purpose.

Early lenses were made from a soda-lime-silica glass, the batch being made up of 350–80 parts of soda-ash and 180–230 parts of limestone to 1000 of sand. Modern optical glasses include a wide range of lead, potash, barium, and other compositions then unknown. Extant early Venetian glasses show a slight cloudiness indicative of devitrification, resulting from an excess of sodium oxide which was introduced (as soda) to lower the temperature of fusion. The medieval glass-makers had difficulty in attaining the melting-point of glass, and kept it as low as practicable; as a result their manufactured product was comparatively unstable. In the seventeenth century one of the most serious obstacles to the perfection of lenses, especially telescope-objectives of large size, was the difficulty of obtaining glass of sufficiently high quality. Flaws and bubbles are often seen in extant lenses of this period.

Methods of working. Besides the professional instrument-makers who manufactured lenses, some of whom, like Eustachio Divini (1620–95) in Italy and Christopher Cock (fl 1660–96) in London, became famous for their telescope objectives, many scientists, including Descartes, Newton, Huygens, and Leeuwenhoek were expert lens-workers. In Italy, Galileo and his pupil Torricelli had done much to develop the art of lens-grinding for scientific purposes. Each expert developed his own detailed practice, though the fundamentals of the art remained the same. First, a plate of glass from the glass-house was roughly polished and examined for flaws. If it proved satisfactory, a circle of appropriate diameter was inscribed on it with compasses and a disk was cut and chipped from the plate (figure 154). It was then necessary first to grind this flat disk to roughly the required curvature, and then to polish it while correcting its shape. These operations were either wholly manual, or effected after about 1640 with the aid of simple machines. No power-driven machinery was employed.

In the manual process, the blank was shaped by grinding on a metal tool—a hemispherically concave or convex disk fixed to the bench. White sand, millstone grit, and emery were the abrasives generally used; as the work proceeded it needed a finer grade of abrasive prepared by levigation, and sometimes a fresh tool was employed at each stage of progress. Hence the accuracy of the curvature of the lens depended on the accuracy with which the tool itself was worked, and on the skill of the operator in manipulating the blank so that it assumed the same curvature as the tool. If the tool was made of iron it was forged, and if of bronze cast, and then turned accurately on a lathe. The imperfections of the lathe itself (p 336) rendered this a difficult art, especially when the radius of curvature required for the tool might be 40 ft or more (figure 156). The glass blank had to be pressed hard down upon the tool with the fingers, or with a small handle cemented to it, so that the process was laborious as well as lengthy.

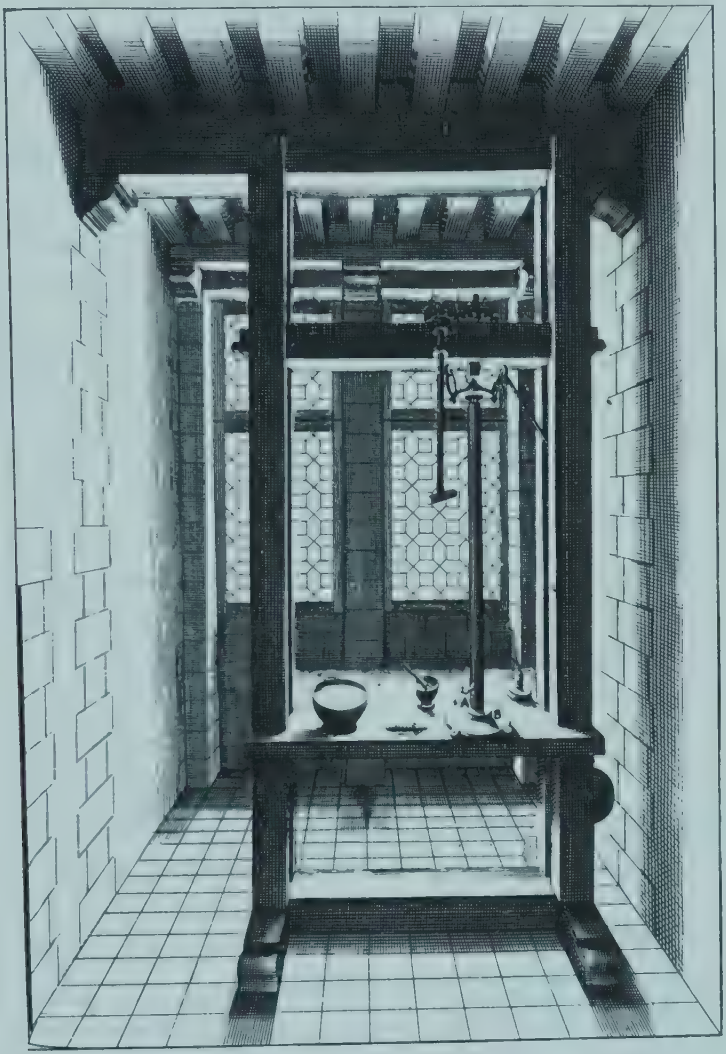

FIGURE 156—*Machine for shaping the forms on which lenses are ground, and working the lenses themselves. By swinging the long vertical rod, which is also rotated by the handle and gears,* A *and* B *are ground spherically convex and concave respectively, the radius of curvature being equal to the length of the rod. 1671.*

To lighten the labour various machines were proposed, similar in principle to machines sketched by Leonardo for use in working metallic mirrors. A simple device used by Huygens involved mounting the blank on a pivoted lever (figure 157) pressed down on the tool by a movable weight. The next stage was to rotate either the tool or the blank—or both—mechanically, as in Huygens's proposed machine of 1665 (figure 157). This principle is employed today. Some seventeenth-century opticians, however, attempted to go farther than this by devising machines that would obviate the need for the dish-like tool and work the glass directly in the manner of a lathe. All these machines were driven by crank-handles, belts, and gearing, thus requiring the services of two men.

The method of working a number of small lenses at once was described by Hevelius (1611–87) as early as 1647. He constructed a kind of vertical lathe, to the mandrel of which a wooden disk could be fitted. The small glass blanks were mounted in pitch on this disk, which had a hemispherical upper surface, and the metal tool was pressed down upon them as they revolved. All were then ground to the curvature of the tool.

After completion of the harsh process of grinding, which removes much of the glass in order to give the blank approximately the required curvature, the very delicate operation of polishing aims at completing the accuracy of the lens and restoring the original smooth, bright surface. A lens without a highly polished surface is quite useless. The lens was still worked in the same manner on a metal tool—either manually or with the aid of a machine—exactly of the required radius; for grinding, the radius of the tool might be slightly greater than that of the finished lens. In the final stages the tool was often lined with pitch, made very smooth and accurately curved while plastic, or with paper after hardening.

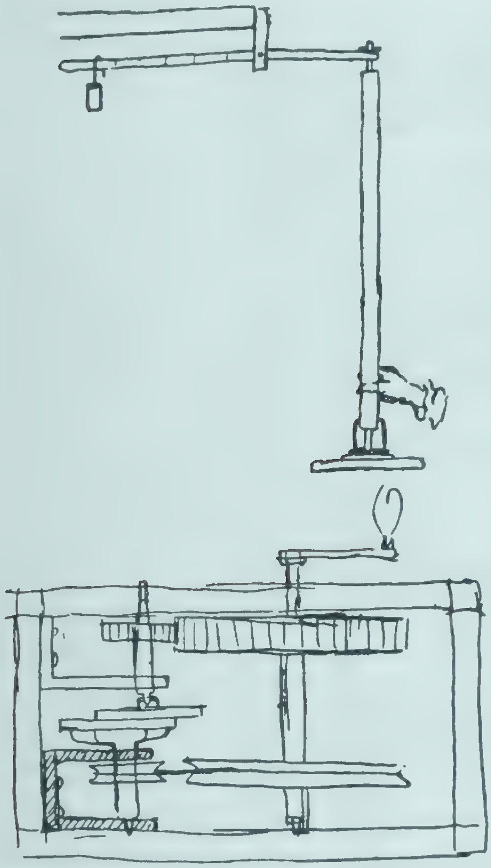

FIGURE 157—*Huygens's lens-figuring equipment.* (Above) *Arrangement for polishing with the* bâton; *pressure is increased by moving the weight to the right,* c *1660;* (below) *polishing-machine; the gear drive rotates the polisher, while the belt turns the lens mounted on the lower spindle. 1665.*

The abrasives used for polishing were tripoli powder (kieselguhr), jeweller's rouge (a form of ferric oxide), or tin-putty (tin oxide), levigated to yield various sizes of particle. Towards the end, the polishing was invariably effected by hand; the work must have been exceedingly slow, tedious, and laborious as a heavy pressure was required. Finally, the lens was buffed on a simple form of lathe worked by a treadle—less effort was required, and intimate co-ordination between the hand, foot, and eye of the operator was important.

Special problems arose when, after 1671, mirrors to some extent replaced lenses. They were all cast in a white tin-copper alloy, to which were added small proportions of antimony, arsenic, and other metals supposed to improve the properties of the speculum. Because the alloy was softer than glass, it was easily spoilt by harsh abrasives or excessively vigorous polishing. But the speculum had one important advantage. By considered use of trial-and-error, and repeated examination of the image, it could be brought to a valuable non-spherical curvature. James Short (1710–68) was the first to 'parabolize' a telescope speculum successfully, and it was to such skill in polishing large mirrors—a protracted and arduous labour—that both he and Herschel owed their unparalleled success with the reflecting telescope. The technique was in principle exactly the same as that used for figuring and polishing lenses.

VIII. WINDOW-GLASS

In the Roman Empire window-glass was uncommon before the third century A.D., although a very limited number of glazed window-slits have been found in houses in both Herculaneum and Pompeii. As these cities were destroyed in A.D. 79, its employment must have begun at least as early as the first century of our era. The Roman glass for windows was either cast or rolled, being sometimes polished afterwards. It was thus more nearly related to plate than to sheet glass.

The evolution of Gothic architecture, bringing about an enormous increase in the window-area of ecclesiastical buildings, stimulated a considerable development of the window-glass industry of the district between the Seine and the Rhine. As one might expect, the earliest window-glass used in Britain appears to have consisted of the little pieces of coloured glass inserted in church windows. They could be made comparatively easily because of their small size, and because impure materials would serve when the final result was to be coloured.

The first Lorraine makers of window-glass came to work in England in 1567. In Scotland as late as 1661 the windows of ordinary country houses were not glazed, and only the upper parts of those of even the royal palaces had glass, the lower ones having two wooden shutters to open at pleasure and admit fresh air.

Some advance in the manufacture of plate glass by casting or *coulage* was made at Venice and afterwards at Nuremberg, but the sheets remained small. By the middle of the seventeenth century there was a demand, especially in France, for large sheets of clear glass for mirrors and the *portières* of coaches. Colbert (1619–83), the great minister of Louis XIV, who came into office in 1661, brought glass-makers from Venice, where glass mirrors had been made from early in the fourteenth century. England was not far behind, for mirrors of blown plate-glass were manufactured at Lambeth about 1670, with the assistance at first of Italian workmen brought over by the Duke of Buckingham. Some of the finest surviving examples of this kind of work are in the Hall of Mirrors at Versailles.

The alternative method of producing plate glass by casting had been developed in Normandy, and in 1676 Colbert, expressly to encourage it, placed the French royal glass-works under the control of the Norman glass-maker Lucas de Nehou, who was expert in the art. By 1691 the casting process had been so improved that plates of unprecedented size were being turned out. Essentially it consisted of pouring the glass upon a metal table, spreading it evenly by rollers, and later treating it by grinding and polishing.

The method that de Nehou laid down at the famous Saint-Gobain works was copied elsewhere and soon became standard practice. The main furnace stood in the middle of the glass-house; round it were grouped ovens or annealing-kilns, called *carquaises*, and others for making frit and calcining old pieces of glass before re-melting (figure 141). The furnace seldom lasted more than three years, and even then had to be refitted every six months.

The melting-pots or crucibles, of the size of large hogsheads, contained about 2000 lb of metal. To assist fusion the charge, consisting of fresh materials mixed with scrap glass, was introduced in a number of stages, a fresh layer being added when the previous one had melted, until the crucible was full. Up to this point the furnace had been kept merely at a red heat. There followed the fining or plaining[1] stage, during which the furnace temperature was raised. Just the right temperature had to be maintained, for if the heat was too low bubbles remained in the metal, while if it was too high the walls of the crucible fused and dripped into the glass. The founding proper took twenty-four hours.

When the molten glass was fit for casting there remained the problem of moving it to the casting table. No entirely satisfactory solution was found. One method consisted of ladling out the more or less liquid glass. In another a cistern was filled in the furnace and allowed to remain there for six hours afterwards; it was then withdrawn by means of a hook on an iron chain guided by a pulley, and placed upon a frame mounted upon a four-wheeled base for transfer to the casting table. Upon reaching the table the removable base of the cistern was slipped off, allowing the molten metal to pour out.

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[1] To plain glass means to make it clear and free from bubbles.

Ultimately it was found best simply to remove the melting-crucible from the furnace and invert it over the casting table. This drastic procedure was not good for the pot, and demanded strong lifting-tackle, but did result in the maximum amount of glass being delivered to the table in prime condition. A consequence of this method was the use of smaller pots for casting plate glass than the stationary ones used for other kinds of glass, so that their weight could be handled more easily.

Upon the casting table the lateral limits to which the glass could flow were fixed by adjustable iron rulers determining the width of the sheet. On these iron side-rails ran a roller which enabled a man to flatten out the glass to a uniform thickness, this being done within the space of a minute to forestall the effects of rapid cooling. Later, as greater quantities of the molten metal came to be handled, the roller was made larger and heavier, so that a crew of three or four men was needed to turn it.

After annealing, which took about ten days, the glass plate had to be ground and polished. It was laid horizontally upon a flat bed of very fine-grained freestone, to which it was cemented with lime-stucco to prevent movement. The stone base of the seventeenth century was changed to a copper one in the eighteenth and to a cast iron one in the early part of the nineteenth. The bed was fitted with a wooden frame having a ledge all round rising up rather more than two inches above the grinding-level.

Grinding was effected with a smaller plate of glass—not more than half the size of that to be treated—which was made to slide upon the one being ground. The smaller plate was cemented to a plank, which in turn was fastened to a wheel of hard, light wood. Workmen pulled the wheel backwards and forwards, and sometimes turned it round, thus causing attrition between the two glasses. The introduction of the steam-engine to supply power for grinding and polishing did not take place until the closing years of the eighteenth century.

This early form of grinding-mill had to be supplied with an abrasive. Water and coarse sand were accordingly poured in, to be followed by finer sand as the work advanced, and lastly by glass powder or smalt. After one side of the plate had been ground, it was reversed and the operation repeated on the other side. It was then ready for the polisher.

An ingenious method of polishing plate glass was common to the European continent and England. A board and a small roller, both covered with felt, were used. The roller was moved by a double handle at each end, and was fixed to the ceiling by a strong wooden hoop which acted as a spring. The action of the workman's arms was facilitated by the spring, because this constantly brought the roller back to the same point.

For many purposes thin blown glass formed into sheets could be used instead of cast plate, which was reserved for purposes requiring extra strength, like coach-windows. Blown glass had the advantage of retaining its original fire-polish, so that no grinding or polishing was necessary. Two specialized methods of making sheet glass were developed, known as the 'crown' and the 'cylinder' processes. The former was the earlier.

Crown glass was originally more or less peculiar to Normandy, but later was made in England also. A gathering of molten glass was blown into a hollow sphere on the end of a blow-iron. To the opposite side of the sphere a pontil or solid iron rod was then attached by means of a nodule of the molten metal. The original blow-iron was broken free, leaving an opening in the globe. Rotating the glass rapidly while still in a semi-molten state caused it to open out into the form of a flat disk, adhering to the pontil by the boss in the centre. Crown glass had two characteristics, the small size of the sheet that could be made by this method, and the unavoidable presence of the bull's eye in the centre.

In Lorraine and the German states the hand-cylinder process was employed to make 'broad glass', sometimes known as German sheet. The method probably developed from that used for crown glass, but was a marked advance upon it. If a large globe of glass such as was used in the crown method was made to swing freely it extended into a cylinder; in practice, pits were provided to enable the glass-makers to obtain extra length. The weight of glass used was from 20 to 40 lb according to the size of cylinder required. Cylinders were made from 12 to 20 inches in diameter and from 50 to 70 in long. When blown, their ends were removed and they were slit lengthwise. Finally, by the simple device of re-heating it in a kiln or flattening-oven the cylinder fell into a flat sheet.

IX. STAINED-GLASS WINDOWS

The making of stained-glass windows is a traditional craft which early achieved results of great beauty. Lethaby has spoken of the window of coloured glass as the most perfect art-form known, and declares that the old glass holds the sunlight as it were within it, so that the whole becomes a mosaic of coloured fire.

The craft developed in the Mediterranean lands in the twelfth century. One of its chief aims was to keep churches pleasantly cool by excluding excess of light. Only small pieces of glass could be produced at that time, but they were sufficient to build up mosaic windows. The irregular bits of blue and ruby glass were pieced together by means of grooved lead, the whole being held in a framework of stone supported by iron bars. Harmonious patterns were formed in this way. To soften and subdue the light still further the glass was often shaded with a monochrome pigment of brown, consisting of powdered glass and oxide of iron, with Senegal gum as an adhesive. In England twelfth-century examples of mosaic medallion windows are to be seen at Canterbury, York, Lincoln, Dorchester (Oxfordshire), Wilton, and Rivenhall.

During the next century the glaziers produced larger windows, with freer use of figure subjects. In England, with her grey skies, the need for more light was felt and in consequence the grisaille style was evolved. Grisaille work gave beautiful effects of opalescence and mother-of-pearl, with delicate decoration of foliate designs and geometrical patterns. The Five Sisters window in York Minster is an outstanding example of this kind of work, and there are other excellent ones at Salisbury.

A noteworthy discovery made early in the fourteenth century was that glass could be stained yellow with the oxide or chloride of silver, giving a full range of tones from lemon to orange. As other colours were added to the palette of the glass-stainer, the 'decorated' period (*c* 1280 to *c* 1380) proved a brilliant one in stained glass. Heraldry figures prominently in windows, especially in England, Germany, Flanders, and later in Switzerland.

In the course of the fourteenth century magnificent stained glass was made for many of the great churches in France, including Chartres, Évreux, Beauvais, Rouen, Limoges, Carcassonne, and Paris. In England the east window of Gloucester Cathedral is of this period; it is the largest in the country, being 72 ft by 38 ft. Other English cathedrals, and the chapels of the colleges at Oxford and Cambridge, were similarly enriched at this time.

The fifteenth century, in which the distinctively English style of architecture known as 'perpendicular' developed, was a most prolific period for stained glass. Colour-schemes grew ever lighter, and shading was kept luminous. Inscriptions were no longer scratched in enamel brown, but were done in dark lettering on a light ground. The abrading of ruby and coated blue gave new effects. A more natural way of representing flesh-painting was obtained by using a wash of enamel colour upon white. One of the most brilliant uses made of these improved technical resources was in the introduction of an increasing number of coats of arms and other heraldic devices.

The last great period for stained glass was the first half of the sixteenth century, the age of the Renaissance. Designs spread over the whole window, and large pieces of glass were used without regard to the curbs and discipline of leads and mullions. Landscapes were painted with heavy smeared and stippled shadows. The windows of Fairford, Gloucestershire, and the noble glass of King's College, Cambridge, belong to the earlier and better part of this period. By 1550 a severe decline had set in, with the technique of oil-painting eclipsing the true nature of stained glass. The introduction of chiaroscuro and similar devices hastened the fall into a dismal period of abasement.

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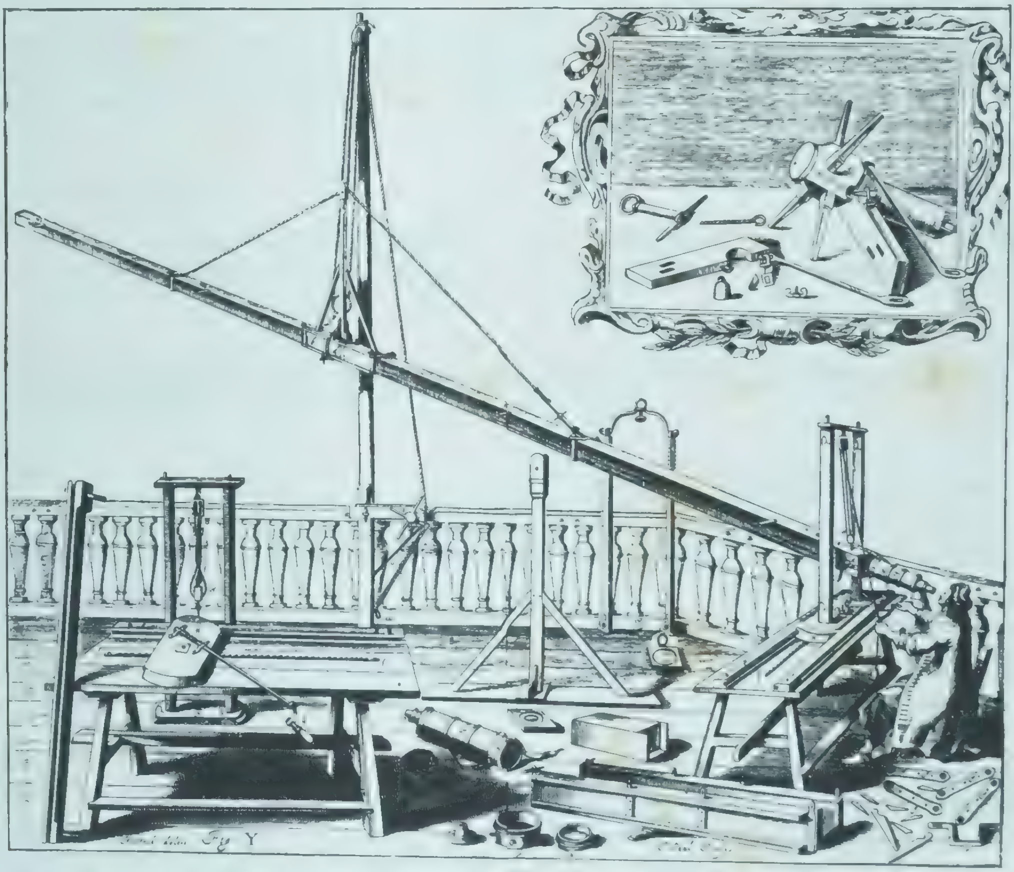

Hevelius's 60-ft astronomical telescope, 1673. The rectangular tube is made from wooden planks; the separate eyepiece N *from vellum-covered pasteboard with wooden mounts. An objective-glass* O, *also mounted in wood, lies on the floor. The telescope is adjusted in azimuth by a rack on the stand, in altitude by the suspending-pulleys and others on the stand* (pp 233, 634–5).

10

BUILDING CONSTRUCTION

MARTIN S. BRIGGS

I. ITALY

THE Renaissance revived interest in the classical learning of Greece and Rome, largely forgotten or neglected in the preceding centuries. It had its origin in Italy, particularly in Florence. It made itself felt in literature during the fourteenth century, but in architecture its beginning is usually associated with the visit of the youthful architect Brunelleschi (1377–1444) to Rome about 1402. He was seeking ideas for the design of a dome for the unfinished cathedral of Florence, then the subject of public competition. He certainly studied the ruins of ancient Roman buildings at first hand, and he won the competition. His dome was duly erected and is still standing; but, despite the popular belief that his antiquarian studies accounted for his triumph, his steeply pointed double dome, the first major work of Renaissance architecture (p 248 and figure 158), cannot have had a Roman origin, for there are no Roman or Byzantine double domes, and its prototype is probably Persian.

Brunelleschi acquired an intense interest in Roman architecture, and was among those who spread a fashion for reviving it in Italy, where Gothic architecture had never aroused the keen enthusiasm that marked its development elsewhere in western Europe. In 1414 an ancient manuscript containing the lost text of Vitruvius on architecture and building construction (freely quoted in volume II) was discovered in a Swiss monastery. In 1486 the work appeared in print and increased the interest in ancient building construction.

By the mid-fifteenth century Gothic architecture had gone out of fashion almost completely in Italy, except at Venice, and the forms of ancient Roman architecture, adapted to suit modern conditions, had taken its place. The movement did not affect the buildings of other countries for at least another fifty years, and even then was confined to minor details of design and ornament. In England, small examples of Italian decoration appeared, here and there, early in the sixteenth century, mainly in and around London in churches and mansions erected by the Crown or by noblemen (for example, in Wolsey's work at Hampton Court); but its full effects were not felt until the early seventeenth century. Away from London, traditional Gothic methods of design and construction continued in all smaller buildings, such as manor-houses and cottages, right up to the time of Wren's entry into architecture about 1662.

In this chapter, the buildings of the Renaissance, up to *c* 1700, will be treated in the order in which the new movement penetrated into three important countries: Italy, France, and England. The new influence was felt mainly in two directions: architectural design and building construction. It is only with the latter that we are here concerned, but, to understand the structural changes, the sweeping revolution in design must be realized.

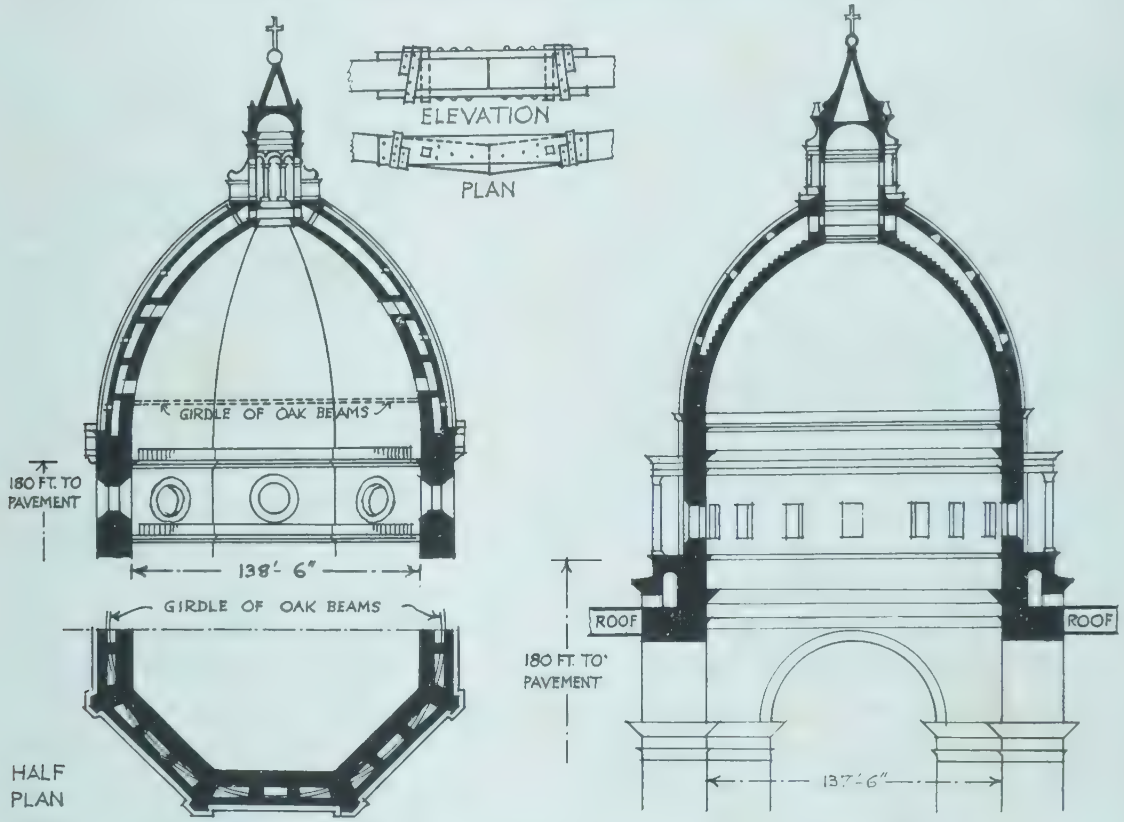

FIGURE 158—*Italian Renaissance dome-construction.* (Left) *The dome of the cathedral at Florence by Brunelleschi, 1420, with detail of its oak girdle* (centre); (right) *dome of St Peter's, Rome, by Michelangelo, 1546.*

In volume II (ch 12) it was explained how the trabeated buildings of the Greeks, with their various 'Orders' of columns, and the arcuated buildings of the Romans, with their round arches and domes and barrel-vaults, gradually came to be succeeded during the Middle Ages by 'Gothic' structures in which the pointed arch was the characteristic feature and in which thin stone-vaulted roofs were carried by a system of ribs, slender columns, and bold buttresses.

Thus, by about 1500, Gothic churches in England, France, and Germany had become mere skeletons of masonry with intervening 'walls' or spaces filled with glass. During the thousand years that followed the fall of Rome, the classical orders of columns—Doric, Ionic, and Corinthian, as defined by Vitruvius—had been completely abandoned and forgotten. They were now revived and introduced into all new buildings in Italy, but they served a decorative rather than a structural or functional purpose.

At Florence especially the arches of the inner courts of the great palaces, as well as the columns separating nave from aisles in the churches, were supported direct on the capitals of Corinthian columns, a fashion used in some of those old Roman halls of assembly known as basilicas. Most of the façades of the Florentine palaces, however, were without columns and were usually crowned with a bold cornice of antique Roman type. One of the finest of these cornices is that of the Strozzi Palace, *c* 1500 (figure 159). It is worth noting that its immense projection over the street, some 7 ft 3 in, is counterbalanced by increasing the thickness of the wall on the inner side, so that the centre of gravity at cornice-level falls well within the margin of safety. The cornice of the Riccardi Palace at Florence (1430) is 10 ft high and has the amazing projection of 8 ft 4 in. All these great palaces were faced with large stone blocks, often rusticated to produce an illusion of colossal strength, though in fact most of this facing was comparatively thin, the bulk of the wall being composed of brick or rubble masonry.

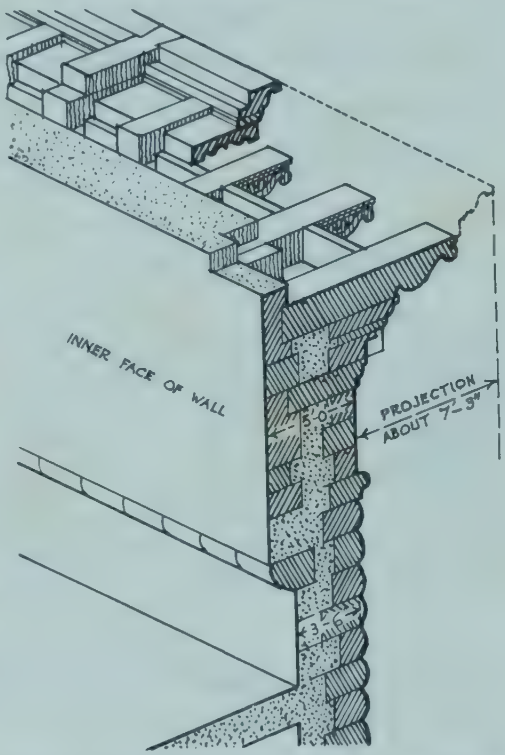

FIGURE 159—*Renaissance masonry. Wall and cornice at the Strozzi Palace, Florence.*

Compared with medieval houses, these Italian palaces, built for rich and noble families, were light and spacious. From the baths and villas of Imperial Rome were derived notions of splendour and formality unknown to the Middle Ages. With the end of feudal strife and the development of refined taste, a demand arose for suites of magnificent apartments, usually with lofty vaulted ceilings. Normally, this type of ceiling was flat and constructed of flat bricks in the Roman way, but continued downwards in the form of a curve or 'cove' at each of the walls (figure 160 A). Where it was desired to give more height to the round-headed windows, the cove was pierced (figure 160 B). In these brick or tile ceilings, the flat bricks or tiles were not bonded or overlapped, and complete reliance was placed on the adhesive strength of the mortar. This type of vaulting may be seen in Rome in the Sistine Chapel and the Farnese Palace. Often, however, the same coved effect was produced in lath-and-plaster, the ceiling being suspended from timber trusses by rods or ropes, as described by Vitruvius (vol II, p 418). Examples may be seen in many fine Renaissance palaces at Genoa.

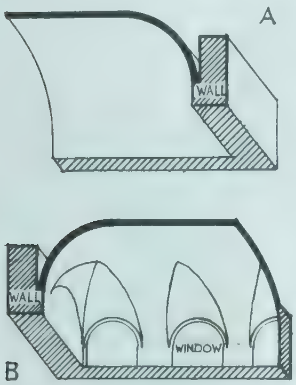

FIGURE 160—*Italian vaulted or 'coved' ceiling.* (Above) *Usual type;* (below) *pierced for windows.*

Brunelleschi's dome (1420–34) at Florence is of two thicknesses of brick with an intervening space, which thus form a cellular system. The two shells of brickwork are connected with each other at each of the eight angles, and at regular intervals between, by solid ribs (figure 158). His specification (1420) describing the construction may be summarized thus: the brickwork of the inner dome is to diminish from 6 ft 11 in at the base to 4 ft 6 in at the crown, and that of the outer dome from 2 ft 6 in to 1 ft 4 in. The intervening space is to be correspondingly increased from 3 ft 8 in at the base to 6 ft at the crown. The 24 ribs uniting the two domes are to be of stone to a height of about 12 ft. The dome is to be built without centring to a height of 60 ft, but thence upwards Brunelleschi vaguely states that 'it shall be continued in such manner as shall be devised by those masters who shall have to do with the building; because, in building, practice teaches what one has to do'. It is significant that practice, not theory, is to be the guide.

An Italian writer of 1820 published an older drawing showing scaffolding supported on raking struts springing from the cornice at the base of Brunelleschi's dome, somewhat like Carlo Fontana's seventeenth-century drawing of the centring used at St Peter's in Rome (figure 161); and Brunelleschi may have used the same method. The construction of St Peter's dome, by Michelangelo (figure 158), is surprisingly like Brunelleschi's and shows no significant advance on it. The dome at Florence, incidentally, is very steeply curved, thus transmitting the weight of the lantern effectively on to the supports.

The arched wooden roof of Santa Maria dei Miracoli at Venice (1480) has a coffered ceiling, also arched; and the timber members of the roof are built up in sections (figure 161). As already explained (vol II, p 442), a roof needs a tie-beam at its springing to prevent it from spreading and thus overturning the supporting walls, while a collar-beam half-way up its height is only a palliative and is often ineffective. At Santa Maria dei Miracoli, iron tie-bars have been inserted across each bay of the church. Such tie-bars may be seen across arches in the courtyards of many Italian palaces.

Curved roofs with built-up timbers are also found on the town-halls of Padua (1306) and Vicenza (1560), and in sundry other buildings in north Italy. In France this type seems to have been evolved independently but concurrently. Similarly the double-slope or mansard roof (p 253) appeared in Italy and England at least as early as in France. The designer of the Paduan roof is said to have copied it from drawings he had made of a palace in India.

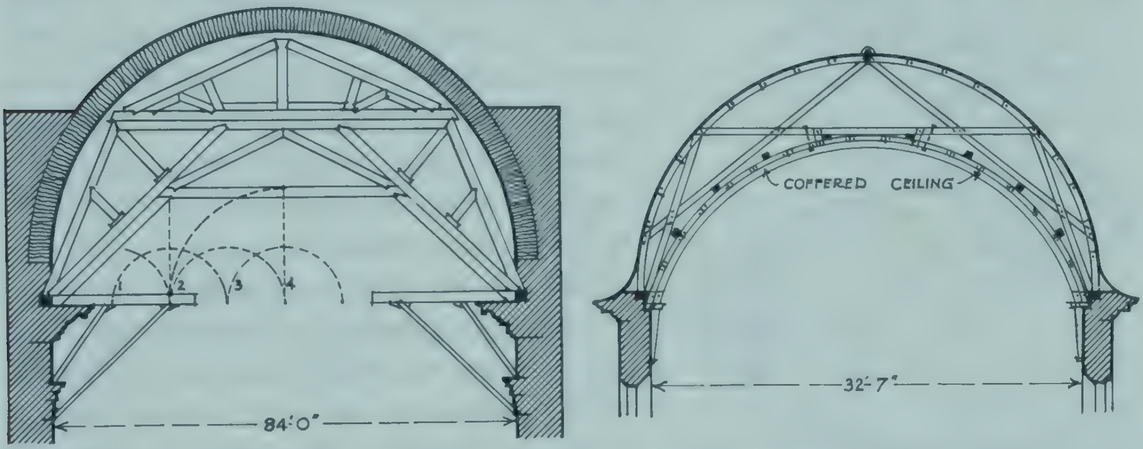

FIGURE 161—*Renaissance carpentry in Italy.* (Left) *Centring for the main arches of St Peter's, Rome;* (right) *roof of the church of Santa Maria dei Miracoli, Venice.*

Many Renaissance churches in Italy, however, had low-pitched roofs with timber trusses, of the type used over Roman basilican churches. In such cases the massive tie-beams are an integral part of the structure. Sometimes these roofs were open, with all the framework visible from below; but many others had elaborately coffered wooden ceilings, another feature inherited direct from ancient Roman times. The example illustrated (figure 162 A), from Santa Maria Maggiore at Rome, shows how the coffering was attached to the coupled tie-beams of the trusses. Here the coffering was painted white, the decorations being gilt.

Instead of stone cornices many Italian Renaissance palaces and churches had very boldly projecting eaves, as at the Pazzi Chapel at Florence (1429), where the immense projection of about 8 ft is obtained by doubling the depth of the rafters at the point where they would be most liable to bend (figure 162 B).

Having glanced at the principal features of Renaissance building construction in Italy, it remains to consider how far these were directly inspired by the revival of ancient scholarship. Round arches, barrel-vaults, and the 'orders' are obviously derived from Roman prototypes. The classical revival, however, went further, and ancient precedent became the rule for processes of actual construction as well as for design and ornament. Vitruvius's book became the architects' bible within a few years from its discovery, and they turned to him for guidance on the burning of lime, the seasoning of timber, or the painting of stucco, with the same complete confidence that they accorded to his pronouncements on matters of taste. Not only Vitruvius but even the Greek Theophrastus (*c* 372–287 B.C.) is quoted extensively by L. B. Alberti (1404–72) in his influential *De re aedificatoria*, first printed in 1485, though his passages on building-materials are descriptive rather than scientific.

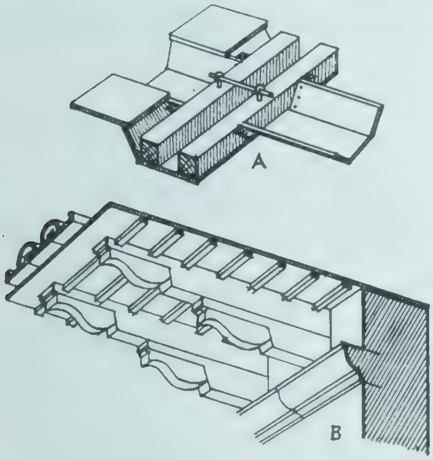

FIGURE 162—*Renaissance carpentry in Italy.* (A) *Coffering of the ceiling, Santa Maria Maggiore, Rome;* (B) *eaves brackets at the Pazzi Chapel, Florence.*

While many architect-antiquarians were rummaging in the Roman ruins in the hope of finding precedents to solve their problems of design, Leonardo da Vinci (1452–1519) was experimenting with every sort of mechanical invention (figure 273); but was he able to contribute anything useful to the science of building, and were there any other pioneers in the same promising field?

Leonardo had no practical experience as an architect or builder, no building or portion of a building being attributable to him, though he made many drawings and sketches of buildings. He does not appear to have made any special study of mathematics or mechanics in early life, but doubtless learnt something from a book on mechanics of the early fifteenth century and from contact with the mathematician Pacioli (1445–1509). Nevertheless, in a manner characteristic of the 'universal man' of his time, his search for knowledge embraced every branch of science. He was not anxious to reproduce antique forms, as were so many architects of his day: flying-machines interested him far more. He experimented with everything that came his way, often abandoning an experiment directly he had shown that its application was practicable.

One such experiment of Leonardo's is illustrated in a drawing showing apparatus for measurement of the tensile strength of wire. On this he makes the comment:

> The object of this test is to find the load an iron wire can carry. Attach an iron wire, about 2 *braccia* [roughly three feet] long, to something that will fairly support it; then attach a basket to the wire, and feed into it fine sand through a small hole at the end of a hopper. A spring is fixed so that it will close the hole as soon as the wire breaks. . . . The weight of the sand and the location of the fracture are to be recorded. Repeat the test several times to check the results.

This simple and ingenious use of sand for tensile tests continued long after his day and, indeed, to our own time—as for cement briquettes.

Many drawings of Leonardo illustrate structural details; but the most important for our purpose is a diagram of loaded beams and struts, one of several in which he attempts scientific solutions of structural problems. These are generally accepted as the first of their kind in modern times. His notes cover the resolution of a single force or velocity into two components, but it is not certain that he had grasped the conception of the resolution of forces as we understand it today.

In dealing with the reactions on supports of loaded bodies, Leonardo approached the problems not only statically as an architect or structural engineer, but also dynamically as in his studies of bird-flight and flying-machines. Examining a rigid structure supported at regular intervals, he argues that 'all bodies which do not bend will exert equal pressures on all of the supports that are equally distant from the centre of gravity, the centre being the middle of the substance of such a body'. The meaning of his phrases is clear, though his manner of expression is often imperfect; lack of a suitable scientific language was his greatest handicap. Elsewhere he considers the effect of applying the load at irregular intervals. His principles are correctly stated, but in some cases his calculations are vitiated by careless arithmetic.

More important, for our purpose, are Leonardo's studies of the strength of loaded struts and pillars, a field in which he had no scientific predecessors. He demonstrates that a bundle of supports bound together is stronger than a single pillar of equivalent sectional area, given adequate strength of the binding material. Again, of two struts of equal height but of different cross-section, he concludes that the strength is directly proportional to the sectional area, and inversely proportional to the relation of height to diameter. Passing then to struts of equal sectional area but of different heights, he argues that their strengths vary inversely as their heights. All this is very sound, but again spoilt by arithmetical errors. In investigating loaded beams, he introduces an ingenious method of demonstration with models built up of several detachable sections. Using this device, he experimented on deflexion. The results he obtained are not accurate, but he did attack such problems of statics scientifically.

Despite Leonardo's pioneering efforts, there is no evidence that architects of his own or the next generation made use of the science of structural mechanics. There was still a gulf between the groping scientist and the actual designers and erectors of buildings. It is known that, by the seventeenth century, bars of metal, wood, and glass were being systematically tested by practical men, but it remains unknown how far the results were transmitted to or used by architects and builders.

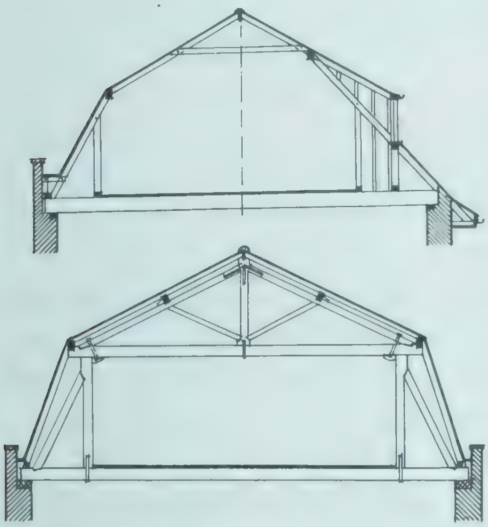

Figure 163—*Mansard roofs.* (Above) *Simple type, with parapet gutter on left side, and with dormer and eaves gutter on right side;* (below) *trussed type with parapet gutter.*

Galileo (1564–1642), who made such important discoveries in mechanics, was the real founder of our modern scientific knowledge of the strength of building-materials, including the principle of cantilevers. However, by the middle of the seventeenth century the chief work in this field was no longer being done in Italy but in London and Paris, and we shall find some of its results in the scientific interests of that remarkable pair of friends, Christopher Wren and Robert Hooke (pp 257, 297).

II. FRANCE

The influence of the Renaissance began to make itself felt upon French building construction in the first years of the sixteenth century. As in England at the same period, it was confined at first to ornamental details in churches and to the country mansions and palaces erected by monarchs and nobles. As in England again, there was a new demand for more spaciousness, light, and dignity in the homes of the wealthy. The change of taste can in large measure be traced to the French military campaigns in Italy between 1495 and 1559, which familiarized the invaders with the novel fashions prevailing there. The actual design and execution of the buildings in France were carried out partly by Italian architects and decorators, and partly by native builders and craftsmen who began to visit Italy for study even before 1500.

Gothic architecture was far more firmly rooted in France than in Italy. Thus it was natural that the first buildings in the new style retained many medieval characteristics, such as steeply pitched roofs, prominent chimneys, gables, and mullioned windows. Vitruvius's work was translated into French and soon became an authority, as in Italy, but it took longer for the introduction of the Roman 'orders' to produce drastic changes of design or structure. The principal innovations in building construction were in roofs, domes, and windows.

For houses and churches alike, the steep medieval roof died hard in France. Indeed, it survived for centuries in a modified form, that of the so-called mansard roof, named from the architect François Mansart or Mansard (1598–1666) who did much to popularize it. This mansard roof, with its double slope (figure 163), was in fact a good deal older than its name would imply. It was used in Italy at least as early as in France, and in England for the great hall at Hampton Court Palace (p 265 and figure 173), constructed between 1530 and 1540. In France it was employed in the portion of the Louvre designed by Lescot in 1549.

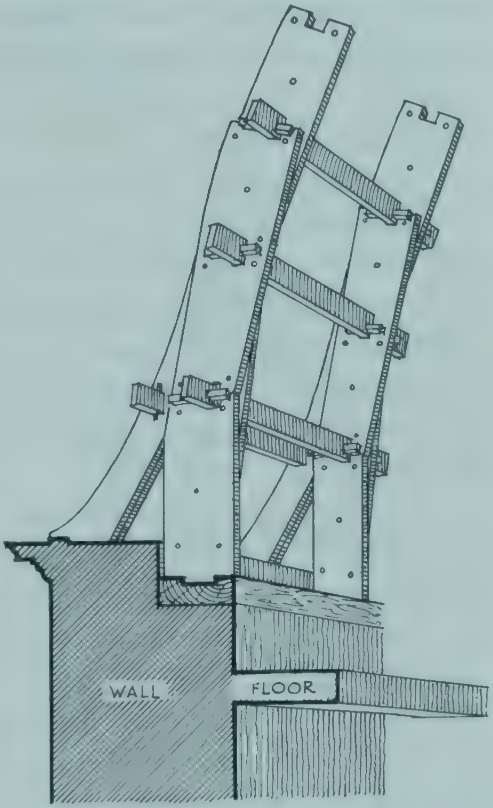

FIGURE 164—*Design for curved roof-timbers built up from short sections, by Philibert de l'Orme. 1561.*

The invention of this type of roof, which is still common throughout Europe, had a functional origin. When the Renaissance reached France, there was a vogue for very high and steep roofs. These provided inadequate space for attics, whereas the mansard, in conjunction with dormers, allowed of good attics with vertical sides, giving an additional habitable room with a considerable saving on masonry walls. For this reason the mansard has remained popular and has led to the semi-bungalow type of house. In America it came to be called a 'gambrel' roof.

Another innovation in roof-carpentry was due to Philibert de l'Orme (1510?–70), who, though he had studied the ruins of Rome, made his reputation in 1561 with his strictly practical book, 'New Inventions for Building well at low Cost'. In it he described and illustrated various methods of constructing curved roofs out of short lengths of light timber, avoiding the use of a tie-beam, an expensive item when spans are large (figure 164). He claimed to be able thus to roof any space up to 300 ft wide, though in one case at least his system failed, the structure collapsing within 20 years.

Most of these French roofs of the sixteenth and seventeenth centuries continued to be covered with slates, as in medieval times. Lead, imported from England, was also used. One of de l'Orme's numerous recommendations was to substitute copper for lead. Slates were also often used for protecting the vertical wooden fronts of timber-framed houses: of this practice there are many examples at Blois. In the royal château of St-Germain, near Paris (*c* 1540), there are flat terraced roofs of stone, carried on vaults strengthened by iron ties as in Italy, and reinforced with buttresses in the French medieval tradition.

Domes were a prominent feature of many French churches of the sixteenth and seventeenth centuries. Wren, who never visited Italy, studied architecture in Paris in 1665 with particular attention to dome-design, though he cannot then have foreseen that he would be called upon to design St Paul's, for the destruction of the old church in the Fire of London had not yet occurred. He was, however, considering the addition of a central dome to Old St Paul's, and embodied it in his design dated 1666.

During the sixteenth century a few small domes had been built in French churches. There were (*a*) a dome covered with slates over the Church of the Visitation, later the Calvinist Church, in Paris (1632–4); (*b*) a high dome over the church of SS Paul and Louis (1625–41) close by; (*c*) another over Guarini's Théatine Church of Ste-Anne-la-Royale (begun in 1662 and since destroyed), which had the Greek-cross plan that Wren tried to use at St Paul's in 1673; and (*d*) yet another over the chapel of the huge Hospital of the Salpêtrière (1657), also in Paris. All these Wren could study, but more important than any of them is the dome of the Church of the Sorbonne in Paris (1635–56), which is double, like those in Rome and Florence (p 246). The outer dome is of timber and slated; the inner, or structural dome, of stone. The lantern is of timber. The inner dome is about 44 ft in internal diameter and 94 ft above the pavement at its springing (figure 165).

At the abbey church of Val-de-Grâce in Paris (begun in 1645), Wren could have seen an even finer dome, actually in course of construction. Like that at the Sorbonne, it is double, with a timber lantern; and, again like the Sorbonne, the stone attic (parapet stage) of the outer drum rises as high as the crown of the inner structural dome of stone, thereby helping to resist its outward thrust. This dome is about 56 ft in diameter, and its springing is 105 ft above the floor (figure 165).

The much loftier dome of the second Church of the Invalides in Paris (figure 165) has some affinity with Wren's work, but in this case any traffic of ideas must have been in the opposite direction, for J. Hardouin-Mansart (1646–

1708), grand-nephew of François Mansart, did not begin it till 1693, when Wren was hard at work on St Paul's; it is possible that Mansart may have seen engravings of Wren's 'Rejected Design' (1673), and certainly both architects must have borrowed ideas from the dome of St Peter's, Rome. Mansart's dome differs in many respects from the dome actually built by Wren at St Paul's (figure 166).

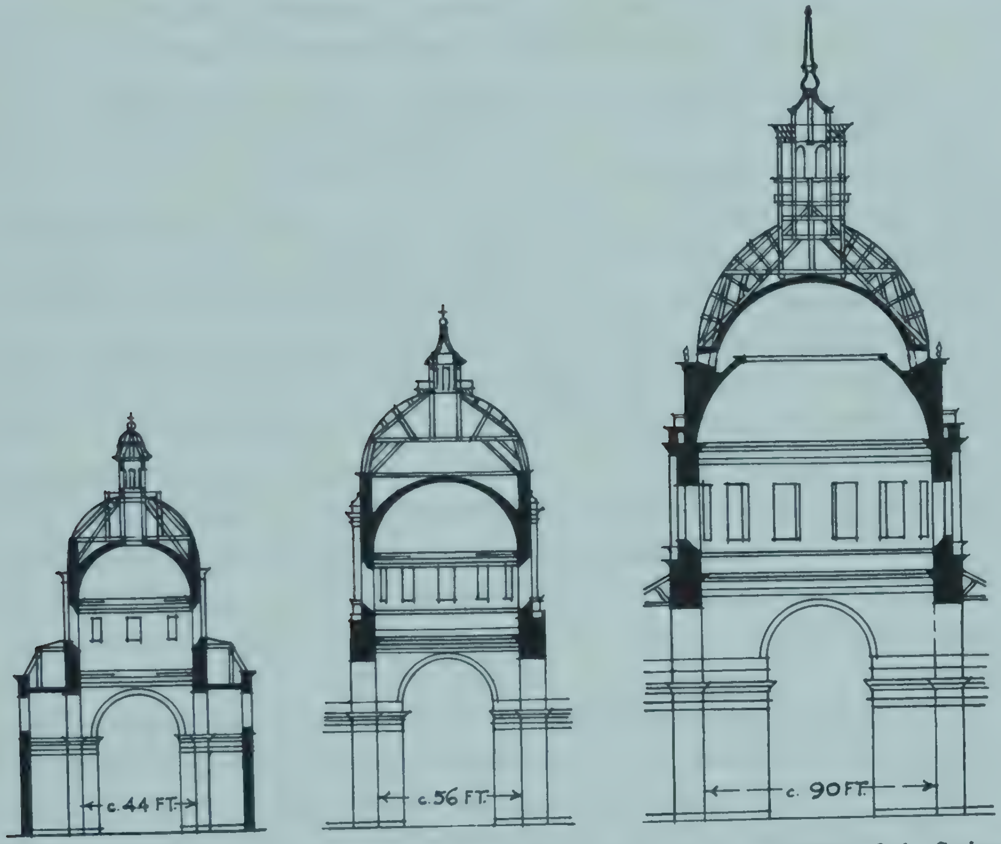

FIGURE 165—*French Renaissance dome-construction.* (Left) *Double dome of the Church of the Sorbonne, Paris, 1635–56;* (centre) *double dome of the Church of Val-de-Grâce, Paris, begun in 1645;* (right) *triple dome of the second Church of the Invalides, Paris, 1693–1706. Drawn to uniform scale.*

The internal diameter is about 90 ft and the height from the floor to the springing is over 140 ft. It is of triple construction, like Wren's. The two lower domes are of masonry, the lowest being pierced by a very large circular opening through which one can see the underside of the middle dome from beneath. The outer dome is of timber covered with lead, like Wren's; but the lantern is of wood, whereas Wren's is of stone and therefore so heavy that his ingenious brick cone was needed to carry it.

Windows in France at this period still retained the medieval subdivision by mullions and transoms. The commonest type was two lights wide and two lights high, divided by a single mullion and transom, forming a cross; hence the French term *croisée* for this kind of window. Gradually, however, the desire for security that had hitherto limited all openings in outer walls to a minimum yielded before the Italian form of large oblong windows. Stone mullions were replaced by wooden ones, and lead cames[1] by wooden bars, until finally the wooden mullions were omitted too. Glass was scarce all through this period. Even in the gorgeous royal palace of Fontainebleau, oiled linen was used in the windows of the inferior rooms almost to the end of the seventeenth century.

Two leading French architects contemporary with Wren were, like him, late converts from science to architecture; yet in neither case have we any conclusive evidence that they employed their knowledge of mechanics in calculations for their buildings. Claude Perrault (1613–88) was trained as a physician, did magnificent work in comparative anatomy, and did not take up architecture until he was 52. At the same age François Blondel (1616–86), formerly a professor of mathematics, became the first director and professor of architecture of the newly founded Academy of Architecture. In the following year he published a book on ballistics and fortification! It is rather in their general intelligence and brilliant inventiveness than in theoretical calculations that these two men, like Wren and Hooke, made use of their scientific training; but in the French Academy of Architecture there were frequent discussions on construction, building materials, and subsoils.

III. ENGLAND

In England, before about 1620, the chief effect of the renaissance of Roman architecture was the addition of Italian ornamental features to buildings of predominantly Gothic design and construction. Between 1617 and 1635, however, Inigo Jones (1573–1652) erected several buildings in which the whole doctrine of Renaissance architecture was proclaimed. Notable among them are the Queen's House at Greenwich, the Banqueting House at Whitehall, and St Paul's Church in Covent Garden. They displayed the Roman 'orders', low-pitched roofs, stone cornices and balustrades, unobtrusive chimneys, regular masonry, large windows, coved ceilings, and indeed all the Italian features already described; while gables, tracery, and other typically English medieval characteristics were generally absent. Such changes as Jones introduced into construction were derived direct from Italy; unfortunately little of his work, so important in the history of English architecture, has survived.

In the time of Inigo Jones, and even later in remote districts of England, old traditions of building lingered on. Not only did Tudor fashions continue in many places, but even Gothic persisted here and there, as in St John's Church at Leeds (1634) and the fine fan-vaulted staircase at Christ Church, Oxford (1630). Far more half-timbered houses in England have survived from the sixteenth and seventeenth centuries than from earlier years, although their picturesque construction is essentially in the Gothic tradition; and this is so likewise in France and Germany. Most of the charming stone manor-houses and cottages of the Cotswolds and the Pennines also date from those two centuries, though their appearance is medieval and their construction traditional.

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[1] Cames are grooved bars of lead holding and connecting adjacent panes of glass in a window.

Very few churches were built in England between 1550 and 1660. The number of parish churches was already adequate; many monastic churches became cathedrals or parish churches after the Dissolution of the Monasteries in 1536–9, and the civil wars of the seventeenth century, like the Thirty Years War in continental Europe, created disturbed conditions unfavourable for church-building.

It might be expected that the renaissance in English architecture would have resulted in a more scientific outlook upon building construction, but nothing of the sort is discernible before the time of Wren. Inigo Jones, for all his brilliant gifts, was no scientist, and was not even well educated. He came into prominence as a designer of theatre scenery, and as one who had studied the ruins of ancient Rome first-hand. Wren, on the contrary, had already attained a high reputation as an astronomer, geometrician, and all-round scientist before he turned to architecture about 1663, at the age of 31. He was then professor of astronomy at Oxford, and had held a similar appointment at Gresham College, London. His inventions cover an astounding range and enter the fields of astronomy, meteorology, physics, navigation, civil engineering, anatomy, musical instruments, geometry, mathematics, surveying, and draughtsmanship, as well as a host of miscellaneous practical devices. Among the last were a few related to building construction as, for example, 'A Pavement harder than Marble'; 'New Designs tending to Strength, etc, in Building'; 'Building Forts in the Sea'; 'Inventions for fortifying and making Havens'.

At Oxford, Wren must have met John Wallis, professor of mathematics, who was one of the first mathematicians to study the theory of loaded beams, and who translated into mathematical terms the much earlier published designs of Serlio (1475–1552). Wren's contemporary and close friend, Robert Hooke (1635–1703), was an experimental philosopher who showed skill in many sciences, including astronomy, microscopy, physics, and instrument design, and who is commemorated in 'Hooke's Law' of elasticity. He became an architect even later in life than Wren. Yet in their capacity as architects, there is no evidence that either Wren or Hooke made use of his knowledge of statics to calculate the strength of structural members, even in the form of reciprocal diagrams[1] or other semi-graphical methods. Nothing of the sort seems to have been attempted until the nineteenth century. On the other hand, Wren in particular must have developed an acute intuitive sense, enabling him to adapt basic scientific principles to practical problems, and, like other Renaissance architects, he made some use of geometry in structural design. One of his rough sketches for the dome of St Paul's suggests that he was adopting Galileo's theory of the catenary curve, discovered early in the seventeenth century (p 434).

The dome of St Paul's is a landmark in English architectural history, for it was the first to be built in this country. As we have seen, Wren studied dome-construction in Paris, while other celebrated domes—those of St Peter's, Rome, and of Florence, besides the Pantheon in Rome—must have been familiar to him from engravings. The design finally adopted, after several false starts, can only have been derived, structurally, from those older domes which were capable of supporting the heavy masonry lantern, weighing about 700 tons, that Wren had chosen as the crowning feature of the design. St Peter's had such a lantern, and a double dome of masonry (figure 166).

The purpose of the double dome is primarily for effect. If the curve be very steep, the external aspect is satisfactory but the interior effect is not, because the space is funnel-like and dark. Conversely, if the dome be hemispherical its internal appearance is pleasing but externally it is not bold enough. Wren's double dome, the inner being of brick 18 in thick, the outer of timber covered with lead, meets the case. Between the two he built a brick cone, also 18 in thick, to carry the heavy stone lantern. Around the whole structure, at the level of the Stone Gallery, where the bases of the brick inner dome and the brick cone meet, he provided a massive iron girdle or band to keep them both from spreading. At a higher level he fixed two strong iron chains for the same purpose (figure 166).

Repairs in 1922–30 proved that serious damage to the masonry structure caused by settlement could not have been foreseen by Wren, for it is the result of recent disturbance of the subsoil, to which, however, defects in the masonry contributed. Although the piers consisted of a facing of dressed stone with a rubble core, the masonry was better than the average medieval building of walls and piers. Some fractures were certainly due to Wren's use of iron cramps too near the surface of the stone, so that they became corroded. Here Wren failed to apply his own dictum that 'in cramping of stones, no iron should lie within nine inches of the air'.

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[1] Diagrams in which the internal forces in a structure are represented to scale on lines parallel to the members of the structure.

The dome of St Paul's was the chief structural innovation and achievement in English building between about 1500 and 1700. Its erection was not complete till 1710, when the work had been in progress for 25 years. Apart from this great monument, however, the development of English building construction from 1500 to 1700 was gradual and unspectacular. It may be treated here most conveniently under the heads of the various 'trades' or crafts.

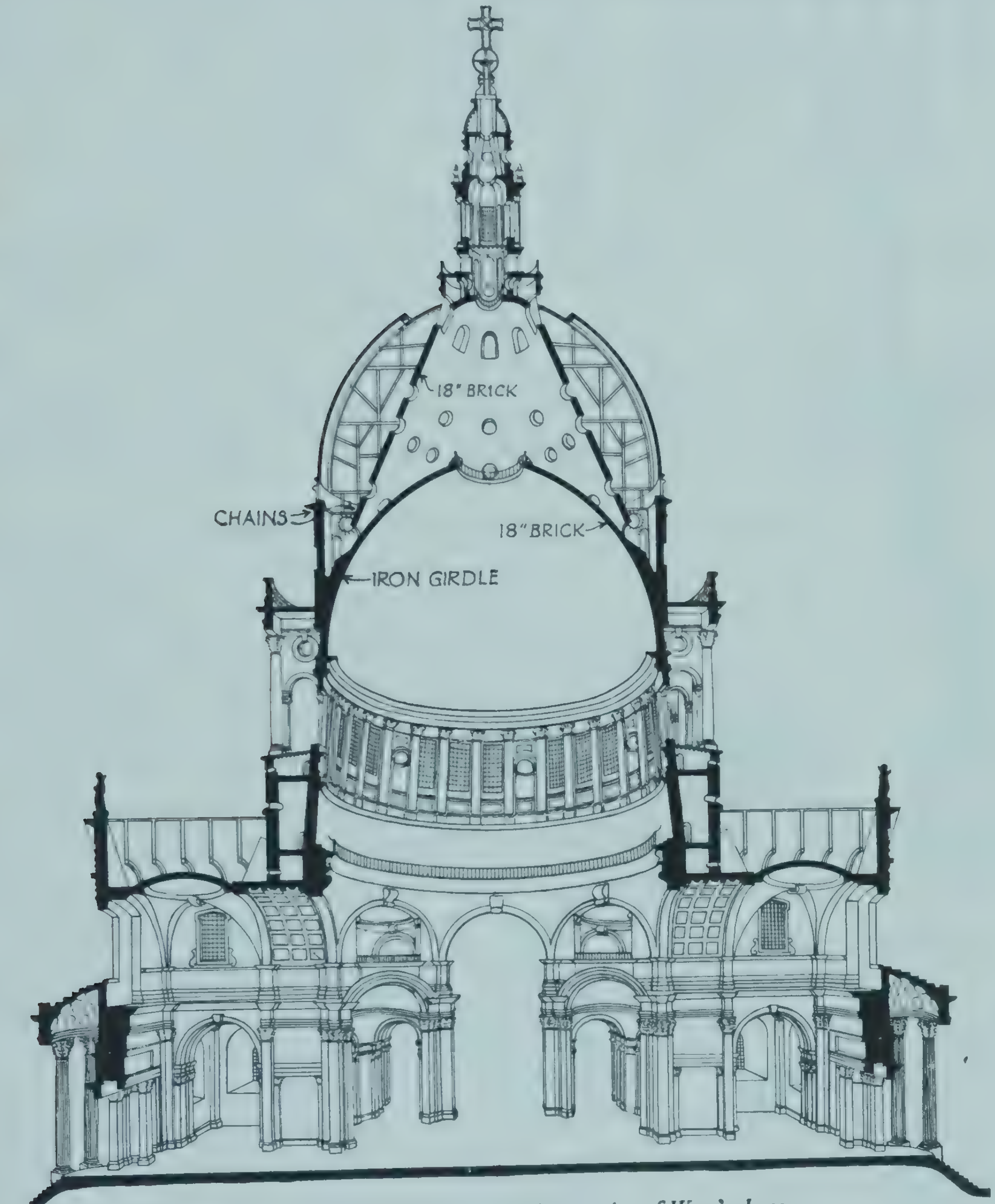

FIGURE 166—*St Paul's Cathedral, London: section of Wren's dome.*

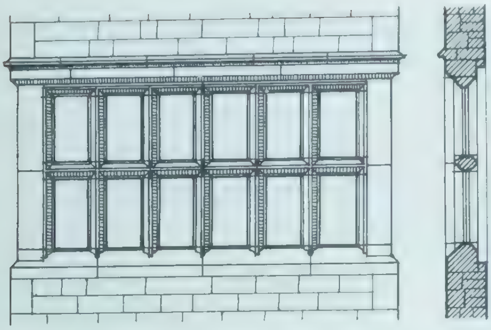

Figure 167—*Construction of stone mullions and masonry in a bay window. Swinsty Hall, Yorkshire. 1579.*

Taking masonry first, changes following the Renaissance were mainly due to changes in architectural fashions. Traceried windows with pointed heads gradually disappeared with other Gothic features. The Roman 'orders' of columns were introduced, together with stone cornices and balustrades. Yet the buildings in which such novelties occurred were comparatively few, and most dwelling-houses erected in country districts, up to 1620 at least, had small windows with stone mullions (figure 167), gables, and other medieval features. The more formal buildings were usually faced with ashlar, the small manor-houses and cottages with rubble (squared, coursed, or even random).

The two chief regions where stone building was practised were: (i) the limestone belt extending from the Dorset coast to the Humber, through Bath, the Cotswolds, Northamptonshire, and Rutland, commonly called the 'Cotswold' region; and (ii) the districts of west Yorkshire, north Derbyshire, north Lancashire, and so on, adjoining the Pennine Range. The stone available in the former area is a fine oolitic limestone; in the latter it is sandstone and millstone grit, with a certain amount of limestone. The famous quarries at Portland—developed by Wren for his churches and public buildings—lie within the 'Cotswold' area, as do the fine Bath stone quarries. Old houses in this region have steep gabled roofs covered with so-called 'stone slates'—actually thin slabs of the same stone that is used for walling and chimneys. These 'slates' were laid 'dry'—that is, without a bedding of mortar—on oak pegs driven into holes bored through them, and were often 'torched' or plastered with hair-mortar on their undersides. Valleys were formed of similar 'slates' specially cut for the intersections of

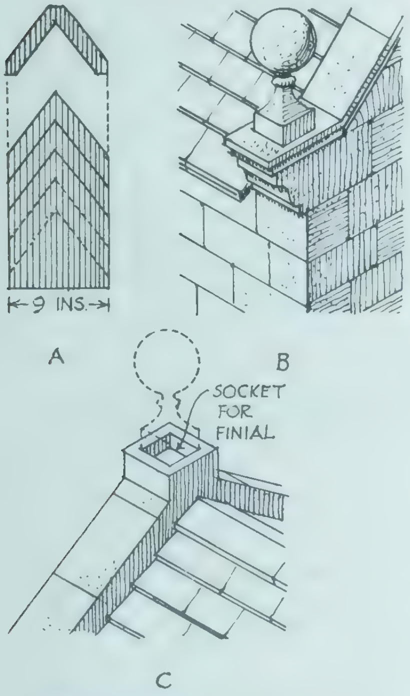

Figure 168—*Details of English masonry.* (A) *Method of sawing Cotswold 'stone slates' from the block;* (B) *Yorkshire stone finial at the foot of a gable;* (C) *the same at the apex of a gable, showing the method of jointing.*

roofs, but ridges were made of stones in the shape of an inverted V, sawn out of a solid block (figure 168). Stone for these 'slates' was (and still is) quarried in October in large blocks, which are then allowed to stand out in the open until the winter frosts disintegrate the layers so that they can then easily be split with a hammer. They are laid on the roof in graded sizes with the largest at the bottom, diminishing in size to the ridge.

The walls of these houses are usually 18 to 24 in thick, with stones laid either in ashlar, coursed rubble, or random rubble; but the ashlar is often a mere facing with rubble behind. Inferior buildings, such as barns, were frequently constructed without mortar, as were the fencing-walls between fields. The heads or lintels over windows and doors were of stone, as were the mullions and transoms of windows. Glazing at first was done in latticed or diamond cames (p 256) of leadwork, but this soon gave place to small rectangular lead cames. Sash-windows were hardly ever used before 1700. Lead gutters and down-pipes were seldom provided, the rain-water from the eaves dropping on to the base of the wall and thus often causing its decay.

Old houses in the Pennine region likewise have 'stone slates', but much larger, thicker, and heavier than the Cotswold type. Roofs are of lower pitch, never more than 45°. Walls are somewhat thicker than in the Cotswolds, and may have an ashlar facing or be made entirely of rubble. In other respects the Pennine houses resemble those of the Cotswold area, but they are rougher in finish, since the material is less tractable. Other districts of England where stone building is traditional are West Sussex (sandstone), Devon and Cornwall (granite), and the Lake District (slate).

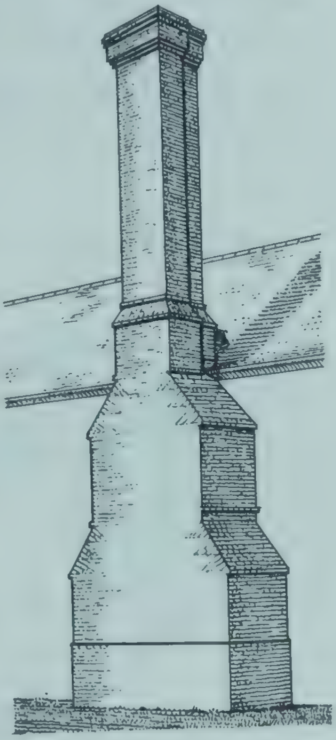

FIGURE 169—*Brick chimney of an old cottage: the type built in Kent and Sussex during the seventeenth century.*

Brick had come into use in England during the late-Gothic period (vol II, p 438), especially in the eastern counties. In the south-eastern counties and in East Anglia it became very popular during the sixteenth and seventeenth centuries, owing to the scarcity of natural building-stone in those parts. Fireplaces and chimney-stacks were now provided in all houses, even cottages. Logs being the normal fuel, fireplaces were very wide, so that much ingenuity was required to reduce the width of brick chimneys from the base to the stack in a series of stages (figure 169).

Bricks were generally laid in English Bond, but Flemish Bond[1] was introduced during the second quarter of the seventeenth century. The size of bricks was prescribed by charter in 1571 as 9 in × $4\frac{1}{4}$ in × $2\frac{1}{4}$ in. Wide mortar joints were used. The introduction from Holland of 'gauged' brick-work, with rubbed bricks and fine white joints, occurred in the second quarter of the seventeenth century, when carved and moulded bricks also came into fashion. Fifty years later, Wren displayed much ingenuity in the use of brick-work, both plain and gauged, notably at Hampton Court. Small yellow Dutch bricks measuring about 6 in × 3 in × 1 in were introduced late in the seventeenth century for paving yards and stables.

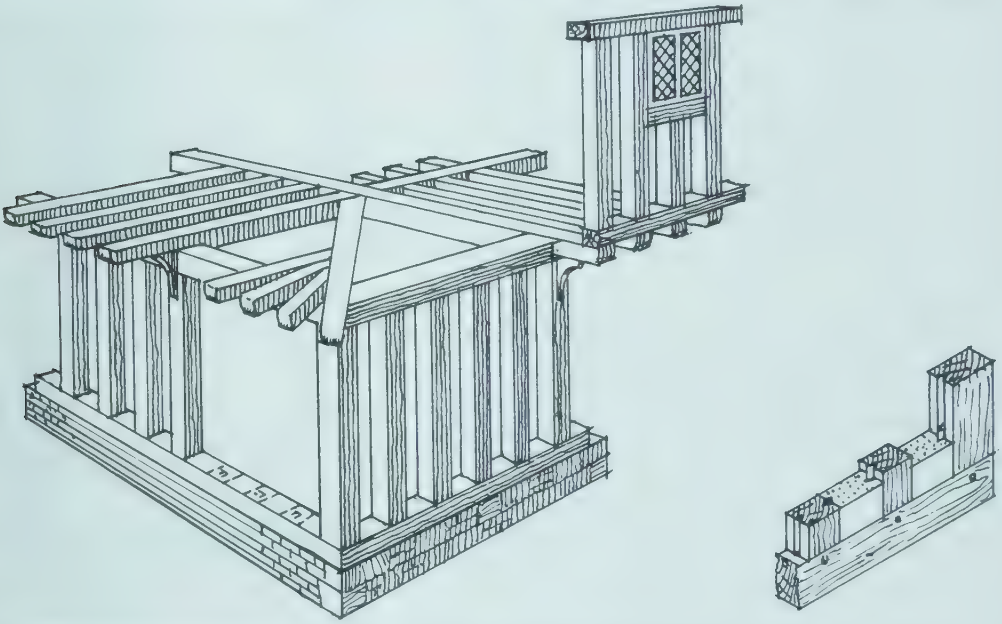

Figure 170—*English half-timber construction.* (Left) *Typical framing of main timbers;* (right) *the intervals shown filled with stone slabs. Great Chalfield Manor, Wiltshire.*

Buildings entirely of timber were still erected throughout the seventeenth century, and later. The chief difference between French and English practice was that in France curved braces were seldom employed, whereas in England they were common, probably because the tall, straight French oak-trees did not produce curved timbers as freely as the English ones. Elm, beech, and sweet chestnut were also used occasionally for timber framing in England.

Figure 170 shows the main principles of construction. Heavy storey-posts,

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[1] In English Bond courses composed entirely of headers alternate with courses composed entirely of stretchers. In Flemish Bond each course consists of alternate headers and stretchers, every header being set in the middle of a stretcher in the course below and the course above.

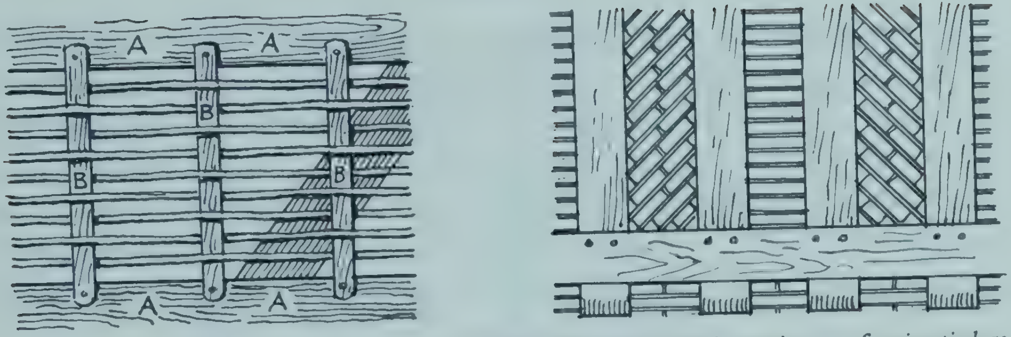

FIGURE 171—*English half-timber construction.* (Left) '*Wattle-and-daub*' *covering.* AA, *framing-timbers;* BB, *laths.* (Right) *panels filled with brickwork.*

8 or 9 in square, were let into a sill-piece resting upon a low brick or stone plinth-wall. The posts at the angles were larger than the others, and were formed from the butts of trees placed root upwards, the top part curving diagonally outwards to carry the angle-posts of the upper storey. Across these were laid beams projecting about 18 inches in front of the framing below, those at the angles being laid diagonally and showing within the house. Into these beams others were connected longitudinally, and to the latter were tenoned floor-joists, projecting the same distance as the main beams.

The framing of the upper storey resembled that of the lower, the plate and the sill being laid upon the ends of the overhanging timbers. The house in its first

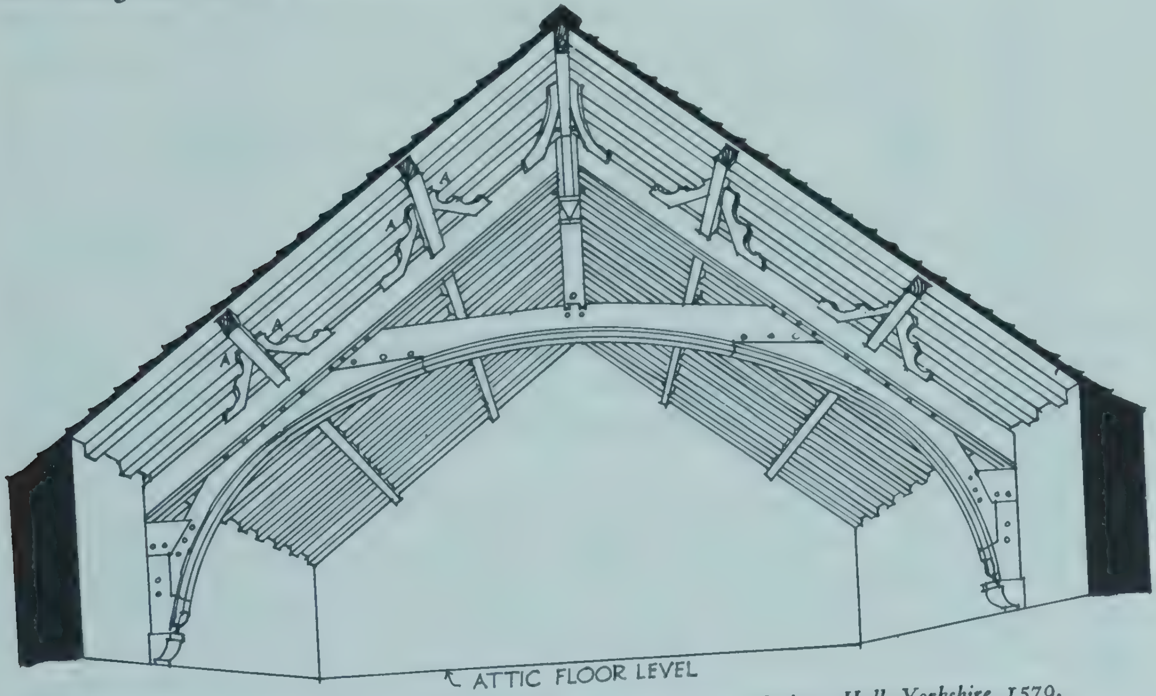

FIGURE 172—*Roof-construction in oak; note the wind-bracing* AA. *Swinsty Hall, Yorkshire,* 1579.

stage of construction was a mere timber skeleton which, until the framing was well advanced, had to be propped and stayed externally. In many examples the slots to receive the stays are still visible in the larger timbers of the lower storey. The spaces between the main posts were filled with uprights about 8 or 9 in wide, and about the same distance apart. In later work they were spaced more widely and curved braces were introduced, especially in the west midlands from Worcestershire to south Lancashire, where they formed elaborate geometrical patterns. At the time of the Fire of London in 1666, most of the houses were timber-framed and it is estimated that 13 200 of them were destroyed. Staple Inn in Holborn (1581) fortunately survived. Thereafter timber buildings were prohibited in the City.

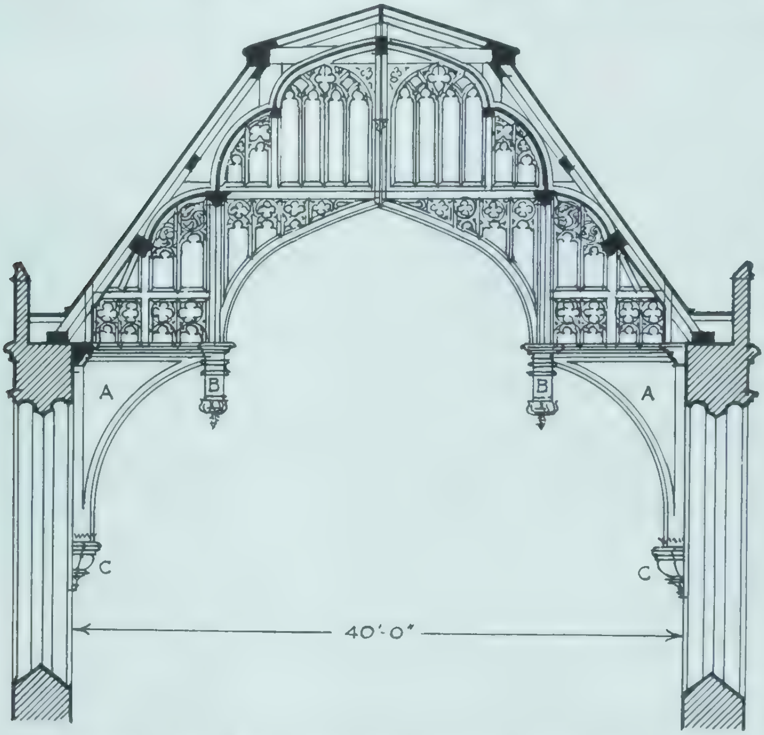

FIGURE 173—*Hammer-beam roof of the Great Hall, Hampton Court Palace, c 1531–5. Typical Renaissance features are the double slope and the ornamentation of the spandrels* (AA), *the pendants* (BB), *and the corbels* (CC).

These so-called 'half-timbered' structures were finished externally in various ways (figure 171). Sometimes the spaces between the various posts and beams were filled in with wattles (hazel-sticks ½-in to 1 in thick, with the bark left on) and laths, smeared with clay mixed with chopped straw, and finally plastered over, flush with the woodwork. The plaster was of lime and sand mixed with hair or chopped hay or cow-dung; it acquired a tough, leathery consistency. Alterna-

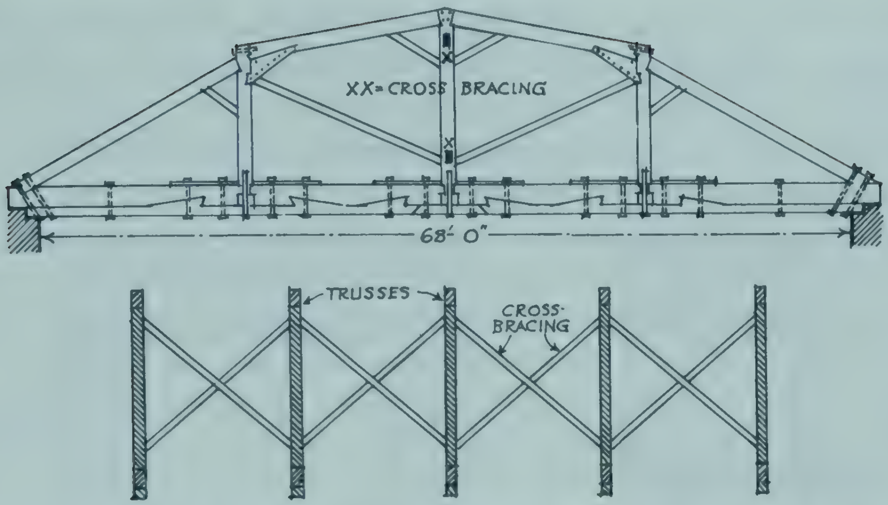

FIGURE 174—*Design for the composite roof-trusses of the Sheldonian Theatre, Oxford, by Wren.* (Above) *Elevation of a single truss;* (below) *cross-bracing between the trusses.*

tively, the whole exterior of the building might be covered with vertical tiles. This method was common in Kent, Sussex, and Surrey; but where the tiles have rounded ends ('imbricated') they are probably of later date. In Essex, Hertfordshire, and Middlesex, weatherboarding was largely used as external covering. This practice was carried to America by the Pilgrim Fathers, becoming a characteristic feature of New England houses. In England, the boards were of oak or elm, about 9 in wide, nailed to the intermediate posts of the framing, each board overlapping the next by 1–1½ in.

Except for the low-pitched roofs introduced from Italy by Inigo Jones, which might have been designed by Vitruvius himself, there was no great change in English roof-design before Wren. Gothic trusses with curved braces continued to be made, as seen in a Yorkshire farmhouse of 1579 (figure 172), which also has lateral ornamental wind-bracing of the type often found in Gothic churches. Hammer-beam roofs, too, were occasionally built as late as the seventeenth century. That at Hampton Court (figure 173) was erected in 1531–5 and is essentially medieval in construction, with Renaissance ornament in its spandrels, pendants, and corbels. It also has the double slope associated with the mansard truss.

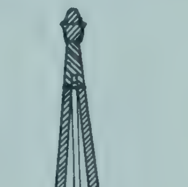

FIGURE 175—*Chichester Cathedral spire, showing Wren's 'pendulum'.* (A) *'Pendulum', 80 ft × 13 in × 13 in;* (B) *'platforms';* (C) *iron weight.*

Wren's roof for the Sheldonian Theatre at Oxford, designed in 1663 (soon after he had turned from astronomy to architecture), marks an innovation regarded by contemporaries as one of the wonders of the age. Following the fashionable taste he took as model for his building the ancient theatre of Marcellus in Rome (11 B.C.), which was open to the sky—a manifest impracticability in the English climate. Wren's building had the enormous width of 68 ft—far too great to be spanned by any normal form of timber construction. In 1663 he had not yet visited France (p 254), but he may well have seen Philibert de l'Orme's book (p 253) on built-up timber trusses for wide spans. At any rate, he evolved a most ingenious design for a truss composed of timbers of reasonable length, dovetailed and tenoned into each other (figure 174), and bound together

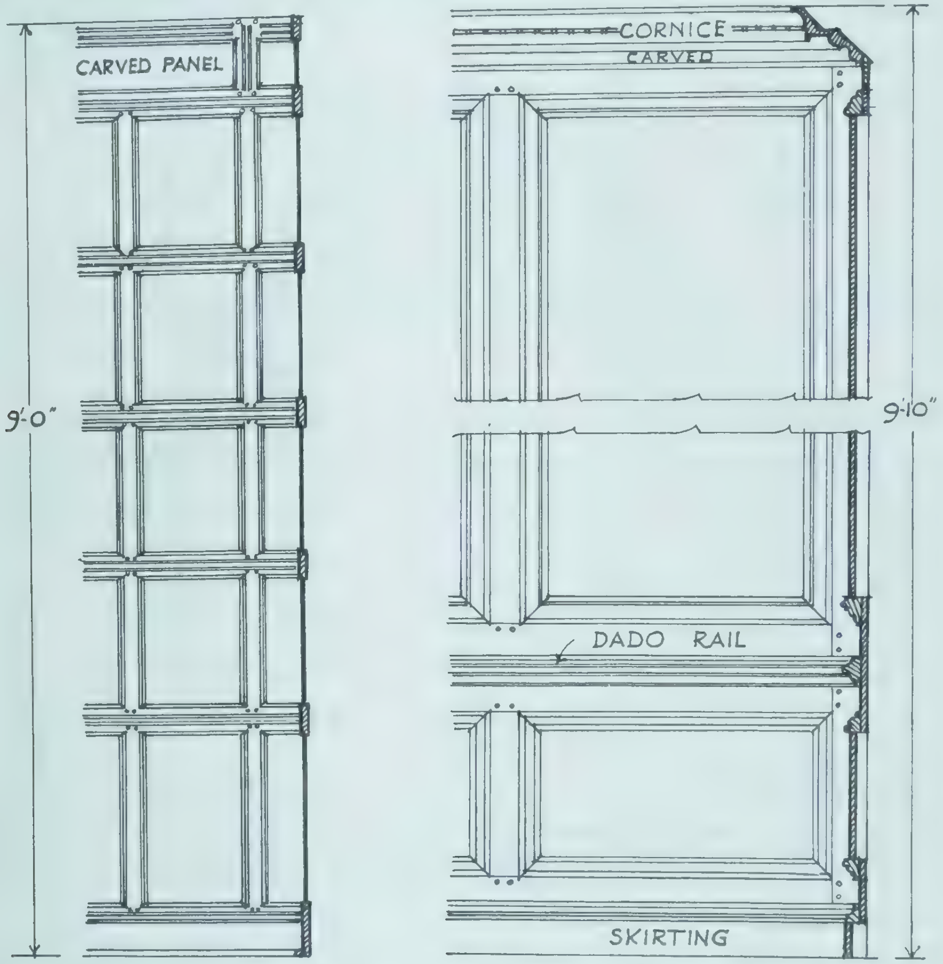

FIGURE 176—*English wall-panelling.* (Left) *From Swinsty Hall, Yorkshire, 1579;* (right) *from Clifford's Inn, London, 1686–8. Note the differences in size, projection, and character of the panels, and the wooden pegs used in the framing.*

by a number of heavy iron bolts, straps, and plates. The trusses were stiffened laterally by a system of diagonal cross-braces. This roof, with its double slope, recalls the mansard type.

In 1694 Wren was called upon to repair the Gothic stone spire of Chichester Cathedral, and showed his scientific ingenuity in a unique structural device. In order to neutralize the effects of frequent gales he suspended a colossal timber pendulum, by means of an iron ring, from the stone finial forming the apex of the spire. This was a single piece of yellow fir,[1] 80 ft long and 13 in square, loaded at its foot with a lump of iron (figure 175). To this pendulum he fixed two stout oaken platforms, the lower one about 3 in smaller, and the upper one 2¼ in smaller, than the masonry walls of the spire. When the wind blew hard on one side of the spire, the pendulum touched the masonry on the lee side and the space on the windward side increased; when the wind dropped, the pendulum returned to the perpendicular. This device proved entirely successful until 1861, when the tower and spire collapsed and were rebuilt.

Great changes took place in the craft of joinery during the seventeenth century. The narrow and inconvenient stone spiral staircases of Gothic times gave place to wide, easy, and handsome staircases of wood. Mullioned windows were used by Inigo Jones for the Banqueting House at Whitehall and the Queen's House at Greenwich, but sashes, said to have been introduced from Holland by William III, were installed by Wren at Whitehall Palace in 1685. They had cords and brass pulleys. Wall-panelling during the Elizabethan and Jacobean periods continued to have very light framing (about an inch thick), delicate mouldings, and rather small oblong panels usually about 18 in high by 12 broad. From the time of Inigo Jones onwards, the size of the panels was greatly increased. They had sloped margins, and boldly projecting mouldings were fixed round them instead of the smaller mouldings formerly worked on the edges of the framing (figure 176).

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[1] A name variously given to the Scots pine, the Douglas fir, and the white fir (*Abies grandis*).

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Stonemasons at work. From a woodcut of 1568.

II

TOWN-PLANNING FROM THE ANCIENT WORLD TO THE RENAISSANCE

MARTIN S. BRIGGS

I. THE EARLIEST PLANNED TOWNS

WHEN men first came to dwell together in units larger than the family in Early Neolithic times, their settlements had no recognizable order, the dwellings of each family being sited merely for individual convenience. Even within the limits of Neolithic culture, however, the gregarious habits of men led to some sort of pattern, so that highly developed and very characteristically arranged villages were ultimately constructed (vol I, figure 197). With the early city states, which developed into the ancient empires (vol I, p 44), the pattern became more definite. It cannot on that account be said that the forms of such cities were foreseen by town-planners. These patterns must be regarded as a spontaneous expression of the culture in which they arose. The ancient empires were well established before any of their cities developed along predesigned lines.

Although 'town-planning' was not so described until about 1904, and although the art and science that it implies did not become recognized as special subjects of study until later, it originated in remote antiquity. As a science, it consists in preparing plans to regulate the lay-out of a town with a view to making good use of the natural advantages of a site, and to securing favourable conditions for housing, traffic, industry, and recreation. As an art, it seeks to create an effect of dignity, harmony, and beauty. Here we are concerned with the former aspect, and how it was practised in the ancient empires. The present study begins with examples from each of the ancient river-valley civilizations.

One of the earliest was the model industrial community at Kahun in Egypt, some 60 miles south of Cairo, which was built in Dynasty XII (*c* 1900 B.C.) to house workmen erecting a neighbouring pyramid. It was laid out in strictly chess-board fashion on about 20 acres, and contained some 300 dwellings of four or five rooms each. There were also some 10 to 20 larger houses for foremen, and ten mansions for the chief officials. On slightly raised ground was a small public meeting-place. One part of the town was reserved for slaves. The straight streets between the square blocks of houses each had a drain running down the middle, providing the earliest known example of street drainage. The little town was inhabited for only 21 years, while the building of the pyramid was in progress.

We still know all too little of the great civilization of the Indus valley which flourished for about a millennium from 2500 B.C. Its best-known cities are Mohenjo-Daro and Harappa. Their culture is characterized by the extreme monotony reflected in their city plans. These settlements consisted of a citadel, presumably a royal residence, surrounded by numerous uniform dwellings for workers set out on a rectangular plan with little regard to beauty or dignity (vol I, figure 30).

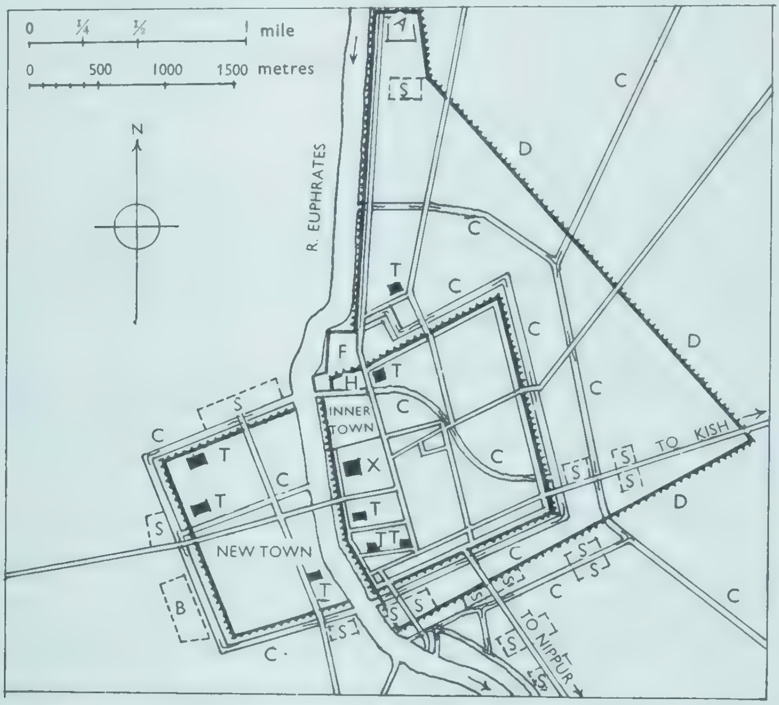

FIGURE 177—*Sketch-plan of ancient Babylon, showing at* A, *Nebuchadrezzar's summer palace; at* B *the burial-ground; at* C, C, C, *canals and moats; at* D, *the outer walls of the city built by Nebuchadrezzar; at* F, *the fortress; at* H, *the 'Hanging Garden'; at* S, *suburban settlements; at* T, *the city temples; at* X, *the 'Tower of Babel'.*

In the third ancient riverine culture, that of Mesopotamia, we know best the great city of Babylon from the eighth century B.C. onwards (figure 177). It covered a considerable area, and was divided by the river Euphrates. Herodotus, writing in the fifth century B.C., says: 'The city stands on a broad plain and is an exact square. In magnificence no city approaches it. It is surrounded by a broad and deep moat behind which rises a wall of 50 royal cubits wide and 200 high.' He explains how the clay dug from the moat was moulded into bricks for the wall, how these were burnt in kilns, and how the bricks were bedded in bitumen from a source eight miles away, where it was found in lumps in a river-bed. He tells how a layer of wattled reeds was laid in every thirtieth course of brickwork, forming a series of dry-courses. The top of the wall was wide enough for a four-horse chariot to turn. The city being cleft into two parts by 'a broad, swift, deep river', the walls were continued down to the bank on each side. The houses were in rectangles bounded by straight streets closed by brass gates where they reached the river-bank. The houses were mostly three or four storeys high [1] (vol I, plate 18).

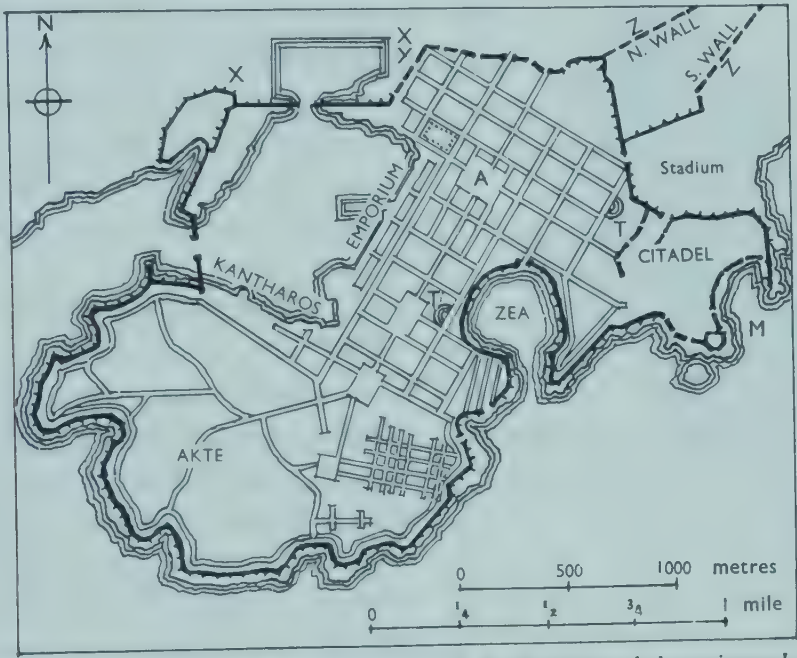

FIGURE 178—*Sketch-plan of the Piraeus, showing the Greek fortifications and the conjectural lay-out of the streets and buildings;* A, *the* agora; M, *the* munichia *(arsenal);* T, T, *theatres;* X, X, X, *modern railway-stations;* Z, Z, *the 'Long Walls' linking the Piraeus with Athens, six miles away. Boat-houses surrounded the* zea *and the* munichia.

Much of what Herodotus says of Babylon is confused, but his general description as summarized above has been largely confirmed by excavation (vol I, figure 286). Babylon, like Assur and Nineveh, had a long processional street or avenue. It is thus in contrast to the town of Ur, which, though possessing about 1800 B.C. many spacious houses (vol I, figure 300), yet had narrow, unpaved, winding streets impossible for wheeled traffic.

In these more ancient riverine empires magnificent results were achieved, but it is not yet possible to trace any development of their plans. Some evolution of town-planning can, however, be discerned in the better-explored Mediterranean world. There, every stage has been found from the first irregular settlements of

Early Neolithic farmers to the most grandiose cities of Imperial Rome of the second century A.D., though until the fourth century B.C. the Mediterranean littoral produced no human aggregate much above a city state.

The capital cities of minor states formed naturally by accretion about a central stronghold or acropolis, which developed as a palace, often in relation to a temple, and an *agora* or open space for meetings and markets. Around this nucleus clustered the dwellings of the population in a roughly concentric manner according to the contours of the site. Such was the recognized but unplanned form of settlements in this early cultural phase.

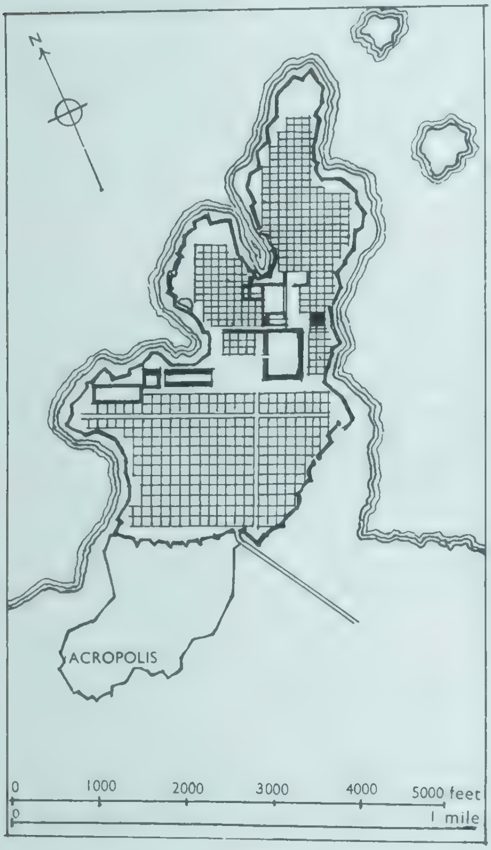

FIGURE 179—*Sketch-plan of Miletos.*

II. THE HELLENIC AND HELLENISTIC WORLD

In spite of magnificent palaces and temple-precincts in the older civilizations, the art or science of town-planning did not come to flower until Hellenic times. Hippodamos (fifth century B.C.), a Greek born at Miletos in Asia Minor, is its first known practitioner. According to Aristotle, who speaks here only of his own Hellenic world, 'Hippodamos introduced the principle of straight wide streets and, first of all architects, made provision for proper grouping of dwelling-houses, and also paid special heed to the combination of the different parts of a town into a harmonious whole, centred round the *agora*' [2]. He laid out the new Greek town of Thurii in southern Italy in 443 B.C. Pericles (*c* 495–429 B.C.) employed him to design the Piraeus, the port of Athens, which he arranged in square blocks so planned that the traffic on the main streets avoided the *agora* (figure 178). This systematic treatment was in contrast to that of Athens, where the splendid groups of buildings on the acropolis and in certain other quarters were very different from the squalid residential districts, planlessly built, with streets narrow, tortuous, unpaved, and unlighted. The *agora*, though surrounded by marble colonnades and fine buildings, served as a market-place and fair-ground, and was normally littered with stalls, shanties, and heaps of goods for sale. These had to be hurriedly removed when a bugle called the citizens to some public gathering. In the narrow streets the shops were open-fronted, as in oriental bazaars today. Similar conditions prevailed in Sparta, chief rival of Athens.

The influence of Hippodamos may, however, be detected in the planning of Selinus in Sicily, which was begun about 408 B.C. There the lay-out is rectangular, in blocks (or *insulae*, as they came to be called in Roman times), regardless of the contours of the site. His share in the replanning of his native town of Miletos (figure 179) after its destruction in 494 B.C. is uncertain, but he must be given some credit for it. Here the *insulae* measured *c* 78 by 96 ft, with some consistency, although the site is irregular in shape. The two main streets were some 25 ft wide, intersecting at right-angles and lined with plain houses of uniform type. Other streets were about 14 ft wide. Several temples occupied the south-east quarter of the city, but they were far older than the gridiron plan of streets and houses, in which no provision was made for monumental vistas.

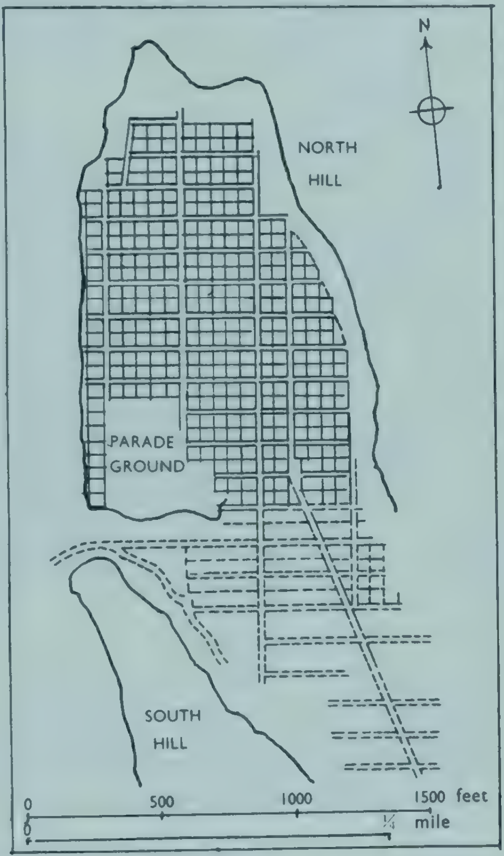

FIGURE 180—*Sketch-plan of Olynthos.*

At Olynthos (figure 180) in Macedonia a new residential suburb was laid out in the same century on a gridiron plan, divided into *insulae* about 283 by 117 ft, with main streets varying in width from about 16 to 23 ft. Each *insula* was bisected by an alley $4\frac{1}{2}$ ft wide, and each semi-block was subdivided into house-lots of some 57 ft square. Each house was planned with a south aspect, and had an internal court paved with cobbles. Most houses were one storey high, with walls of mud-brick on a rubble plinth. A sheltered portico was provided. The main room of the house faced south and was often furnished with a central hearth. There was no provision for sanitation.

The gridiron plan persisted in Hellenistic times. An interesting example is the small town of Priene near Miletos in Asia Minor (figure 181). The site sloped steeply towards the sea from a precipitous rock forming a natural acropolis. Nevertheless, the lay-out was strictly rectangular, with seven main streets running roughly parallel to the slope of the acropolis, crossed by 15 steeply sloping streets. The principal streets were from 18 to 24 ft wide, the others 10 to 15 ft. The whole area was thus divided into *insulae* measuring about 116 by 155 ft, subdivided in the residential quarters into house-lots averaging 58 by 78 ft. Several *insulae* in the central quarter were occupied by public buildings. The total number of dwellings is estimated as between 400 and 500, accommodating a population of about 4000. To keep the plan compact for purposes of defence, no gardens were provided. The normal type of dwelling at Priene, though showing some advance in luxury, resembled that at Olynthos in having a courtyard, a sheltered portico, and one large room. Generally there was a long passage extending through the house from front to back. At Delos, a little later than Priene, many houses had a graceful marble peristyle or colonnade round the courtyard, often with a central water-tank, as in the following Roman period.

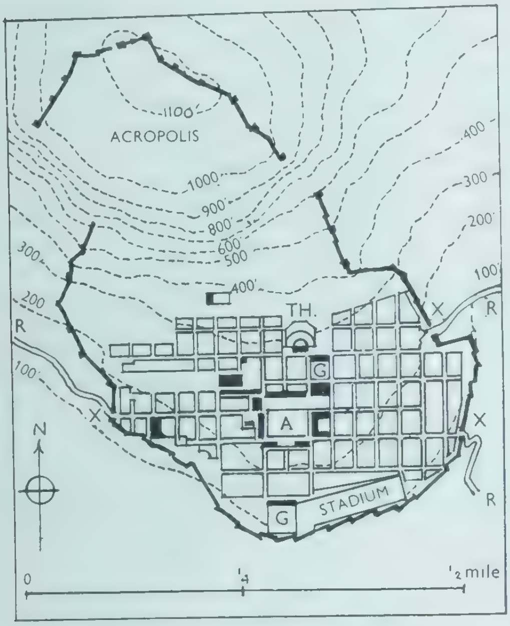

FIGURE 181—*Sketch-plan of Priene, showing at* A, *the agora; at* G, G, *the gymnasia; at* R, R, *roads; at* TH, *the theatre; at* X, *the city gates. The contour-lines show heights in feet above sea-level.*

Better known than these Greek towns is Pompeii, which was destroyed by an earthquake in A.D. 63 and finally submerged in ash from Vesuvius in A.D. 79. The excavation of its buried streets and houses has revealed the complete plan of a Graeco-Roman town, with houses ranging in date from the third century B.C. The lay-out is not strictly rectangular, the *insulae* being slightly trapezoidal, but there was an earlier village on the site, which influenced the plan. The forum measured 500 by 150 ft and contained temples, a basilica, a market, and public latrines. The paving of the main streets was cambered, with gutters at the sides. Pompeii is, however, a more significant example of architecture and decoration than of town-planning. Certain of its houses occupied an entire *insula*, and possessed features not found in their Greek prototypes. Thus planning of the larger dwellings is strictly axial, on either side of a line bisecting the whole block on its longer dimension, namely, from front to back. The famous 'House of the Faun' has a garden surrounded by a colonnade, right across the width of the site, in addition to another peristylar court, and beyond it is the so-called atrium into which the principal rooms faced. Internal gardens were frequent.

Of other Hellenistic cities, one which came to an end in the fourth century A.D. is the frontier fortress-city of Dura Europus, on the Euphrates near Palmyra, which has been well explored. It was on the gridiron plan. The main street was over 36 ft wide; the others were about 20 ft wide, crossed at right-angles by 12 narrow streets.

Ephesus in Asia Minor was monumentally planned around its fine public buildings. It contained large public baths, a theatre, several gymnasia, a stadium, and some imposing open spaces, the great *agora* being about 525 ft square. The long main street, 36 ft wide, was paved with marble, and had deep colonnades on each side, with rows of shops behind them. Colonnaded streets were a characteristic feature, if not an invention, of the Hellenistic period, and the *agora*, a Greek feature, was greatly developed.

Corinth was finely laid out during Graeco-Roman days, with its small but ancient acropolis, and its temple as the focal point. The chief feature of the plan is the enormous double stoa or covered portico, nearly 550 ft long, giving on to a range of 33 shops, each of two chambers. The water-supply of the city was from a perennial source, the poetically famous 'Peirene Spring', in the mountains. It was collected in four parallel reservoirs, discharging through six sluices. Each shop had a square well-pit some 36 ft deep, behind which was a continuous water-channel fed from the spring. It is supposed that the cold running water made the pits cold-storage chambers, as this elaborate system was not applied to dwelling-houses. The date of this remarkable installation is much earlier than the main city plan and is probably fourth or third century B.C.

Antioch was another formally planned Hellenistic city, as was the great port of Alexandria in Egypt, where the chief modern thoroughfare follows the exact line of the old main street running perfectly straight for about four miles. This city was laid out for Alexander the Great by his architect Deinocrates on a sandy strip of land between Lake Mareotis and the Mediterranean. It had a gridiron plan; but of its former glories, which included the celebrated *Pharos* (lighthouse), few traces survive. At Damascus, the 'Street called Straight' was nearly a mile long and was lined with colonnades.

III. ROME AND HER EMPIRE

Town-planning developed rapidly under the Roman Empire, reaching a point of excellence never attained again until the Renaissance (p 285). For various reasons the lay-out of Rome itself (figure 182) did not follow the same evolution as that of other Roman towns, in which the gridiron or chess-board plan was almost universal. It is doubtful whether this very typical Roman plan is due to Greek precedents, or was suggested by ancient Italian towns such as Marzabotto (founded *c* 500 B.C.), or is but the traditional plan of a Roman military camp (figure 183. The Roman camp was square or oblong and divided by two main streets, one running east–west and the other north–south, with the headquarters building close to the point where they crossed). Vitruvius discusses the choice of a site for a new town, giving advice on marshy localities and their drainage, and treats of the planning and erection of fortifications, of suitable aspect for houses, and of the position of public buildings [3].

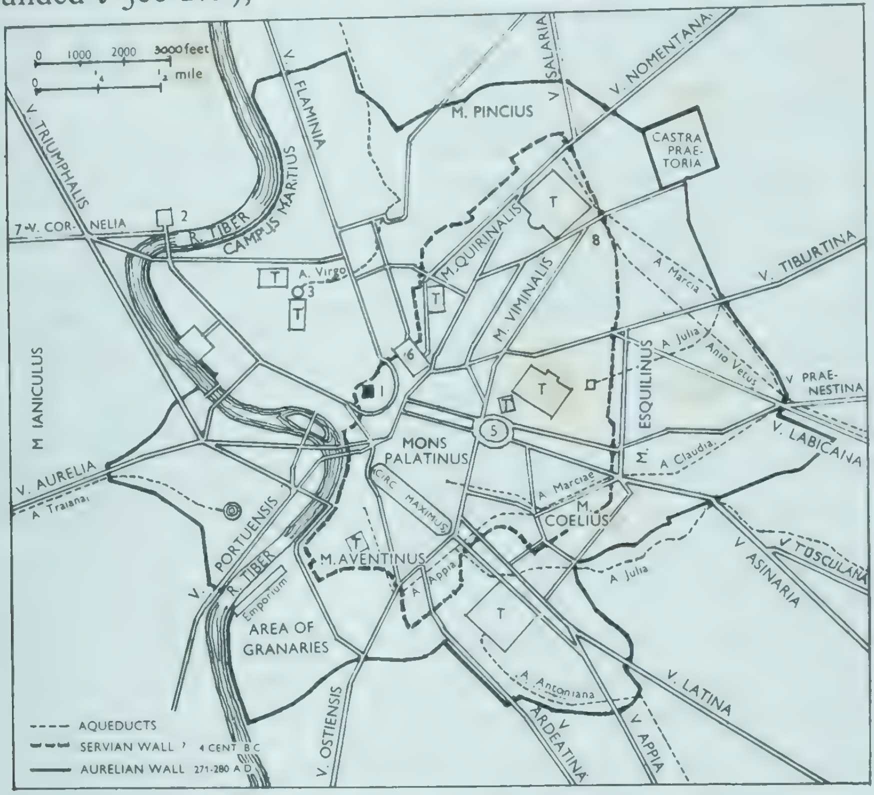

FIGURE 182—*Sketch-plan of Imperial Rome, showing walls, main roads, aqueducts and* thermae *(public baths). The area shown is about nine square miles.* (1) *The Capitol;* (2) *the Mausoleum of Hadrian (Castle of S. Angelo);* (3) *the Pantheon;* (4) *the* Forum Romanum; (5) *the Flavian amphitheatre (Colosseum);* (6) *Trajan's Forum;* (7) *the site of St Peter's;* (8) *the site of the modern railway-station;* TT, thermae.

Roman provincial towns, outside Italy, were either *coloniae*, that is, new settlements for ex-servicemen, or existing towns to which this status had been granted, or *municipia*, the title used for important native towns. In Britain there was only one civil *municipium*—St Albans (Verulamium)—as against four military *muni-*

cipia: Colchester, Lincoln, Gloucester, and York. Of lower rank and much more numerous were the *civitates*, tribal or cantonal capitals. Among the latter were Exeter, Winchester, Caerwent, Canterbury, and Silchester. In general the termination '-chester' in many English place-names stands for Latin *castra*, a camp.

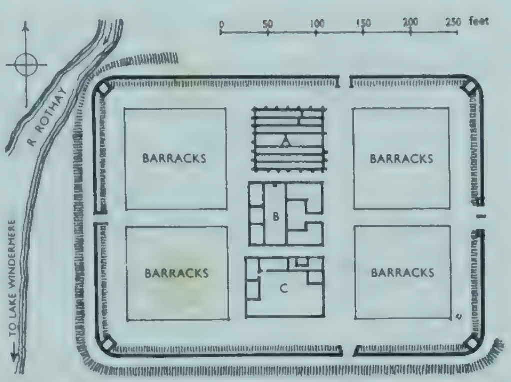

FIGURE 183—*Plan of the Roman fort at Ambleside, Westmorland (second century* A.D.*), showing at* A, *the granary; at* B, *the* principia *(headquarters); at* C, *the commandant's residence.*

Typical Roman towns in Britain are Silchester and Verulamium (figures 184, 185). Silchester was originally a tribal capital, retained as an administrative centre by the Romans and rebuilt on chess-board lines, probably within half a century after the Roman conquest. It contained a forum, a basilica, a large inn for travellers, and public baths. The tiny Christian church was built later. The town stood at an important road-junction, where the Bath road from London branched out into three roads leading to Cirencester, Winchester, and Bath. Yet though divided by straight streets into rectangular *insulae*, the actual siting of the houses on these *insulae* was irregular. Presumably Roman surveyors set out the streets but the native inhabitants disposed their dwellings to suit their individual whims. Whereas in most Roman and Greek towns the houses are packed tightly on the *insulae*, at Silchester they were detached, forming an early garden-city. Hence although the area of Silchester (100 acres) was nearly a third of that of Roman London (325 acres), it contained only 80 houses. The colonnaded forum, 310 by 275 ft, contained shops as well as the 'county offices'. The perimeter of the town is irregularly polygonal and the walls were probably sited upon earlier British earthworks.

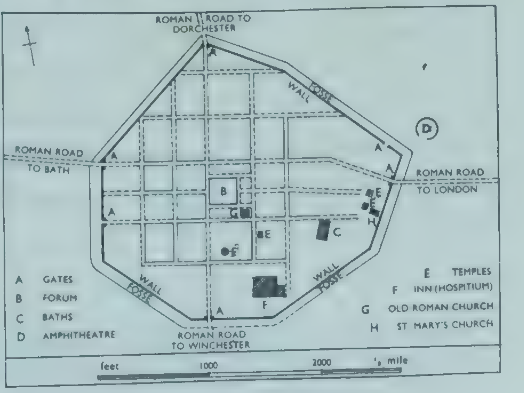

FIGURE 184—*Plan of Silchester.*

Verulamium (figure 185), which covered about 200 acres, was the most extensive Roman town in Britain after London (325 acres) and Cirencester (240 acres). It lay on the Watling Street leading from London to Chester. This road entered the city through the fine south gate, which was flanked by projecting towers and provided with arches for two-way wheeled traffic. The massive

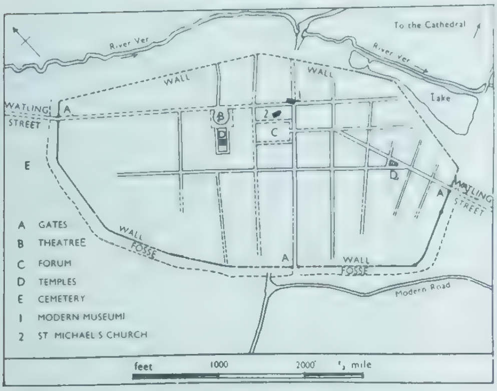

FIGURE 185—*Plan of Verulamium.*

town-walls, strengthened by bastions and a ditch, were of brick and flint and had a total circuit of two miles. They had four gates. Near the forum, which adjoined the intersection of the two main roads, the Watling Street was widened to 35 ft, presumably to provide the equivalent of a car-park. Besides the usual public and domestic buildings of a Roman city, Verulamium possessed the only known Roman theatre in Britain.

Roman London had a population of somewhat under 20 000. Its boundaries are marked by the line of the city wall, much of which is now exposed (figure 186). The landward portion of the wall was probably built between A.D. 60 and 150; the bastions are somewhat later; and the river-wall dates from the latter part of the third century. The wall was of flint, brick, and stone, and its circuit was about three miles. Newgate, the only gate excavated, seems to have had a double carriage-way flanked by two projecting square towers, as at Verulamium (vol II, figure 464). Six main roads converged on London: from Dover (Watling Street), Chichester (Stane Street), Silchester (Akeman Street), Wroxeter and Chester (Watling Street), York (Ermine Street), and Colchester.

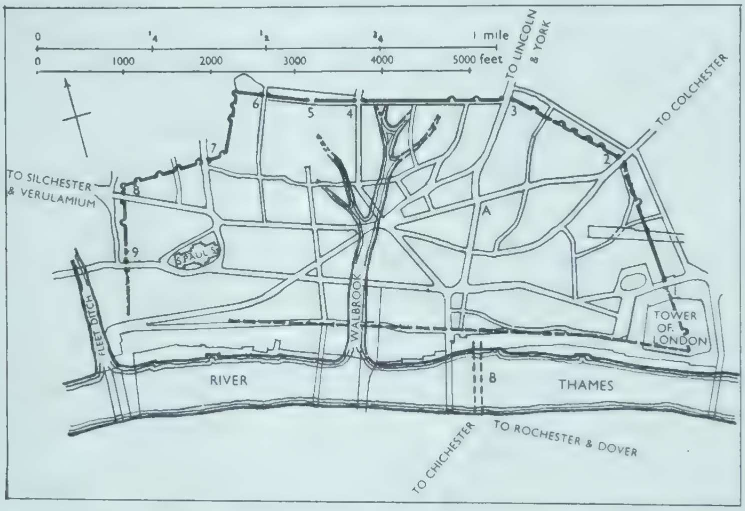

FIGURE 186—*Sketch-plan of Roman London (with the walls in heavy line and the modern streets in thin line), showing at* A, *the site of the basilica; at* B, *the approximate site of the bridge. The gates are* (1) *Tower Postern;* (2) *Aldgate;* (3) *Bishopsgate;* (4) *Moorgate;* (5) *Aldermanbury Postern;* (6) *Cripplegate;* (7) *Aldersgate;* (8) *Newgate;* (9) *Ludgate.*

The city stood on a plateau of gravel with a maximum height of about 50 ft, bisected by the little stream now known as the Walbrook. The original level of the Roman city was 10 to 30 ft below the present street-level. Timber piles have been found along the bed of the Walbrook. *Londinium* was certainly a flourishing place by A.D. 60. There were two cemeteries within the walls, the larger being close to the site of St Paul's Cathedral. The plan was rectangular, but it cannot be reliably restored owing to lack of adequate evidence. The most important building was the basilica.

Of Roman cities outside Italy very few retain any considerable part of their original plan, though some streets in Treves, Cologne, and perhaps Belgrade follow the old lines. The walls of Treves, founded A.D. 2, enclosed 704 acres, so that it was thus more than twice as large as Roman London and 23 times as large as Timgad (below). Constantinople was rebuilt by Constantine in 330 on the site of the old town of Byzantium (figure 187). Its area was extended by a succession of walls in 413, 447, and later. The latest walls were 100 ft high, and had many lofty towers. Its internal planning was formal but not strictly rectangular, owing to the contours, which formed, as at Rome, seven small hills. These were admirable for the placing of the principal buildings. The main streets were arcaded or colonnaded, and were punctuated by at least six splendid *fora*. The famous hippodrome accommodated 100 000 spectators. The system of water-

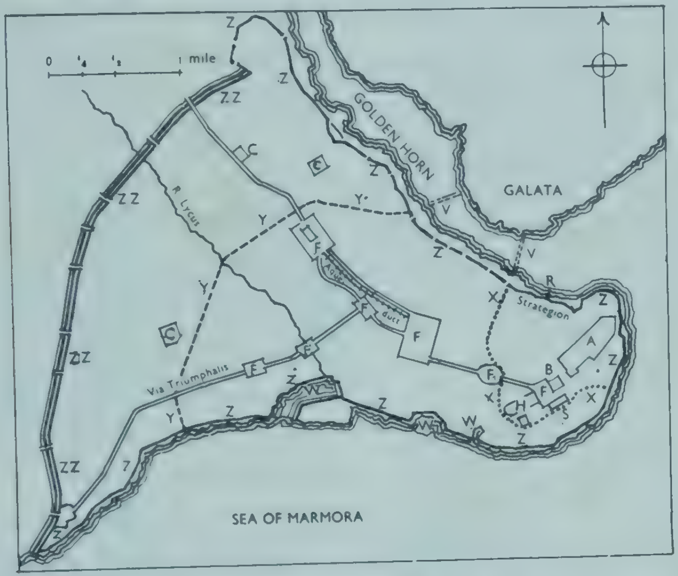

FIGURE 187—*Sketch-plan of Byzantium (Istanbul), showing at* A, *the acropolis; at* B, *S. Sophia; at* C, C, C, *the principal cisterns; at* F, F, F, *the* fora; *at* H, *the hippodrome; at* S, *the* senatus; *at* R, *the modern railway-station; at* X, X, X, *the land walls of the ancient city and at* Y, Y, Y, *those built by Constantine; at* Z, Z, Z, *other fortifications; at* W, W, W, *ancient harbours; at* V, V, *modern bridges.*

supply was notable; drawn from various distant streams and springs, the water was conveyed by aqueducts that ran underground except across valleys. It was stored in open reservoirs or in covered cisterns within the city. Some of the latter are still in use; one has a capacity of 6 500 000 cu ft. The roof of another is supported by 224 columns with triple shafts.

Timgad, in Algeria, founded by Trajan in A.D. 100 as a colony for ex-soldiers, has been especially well excavated and shows the gridiron plan in its strictest form (figure 188). It covers only 30 acres, yet is divided into 132 *insulae*, each some 75 ft square; nearly 20 of them, in some cases combined together, were occupied by public buildings. The remainder were occupied by houses, of which there were about 400. The principal streets were paved and colonnaded. Near the forum were the basilica, a theatre for 3500 spectators, and public baths. The general effect of this gridiron layout must have been extremely monotonous.

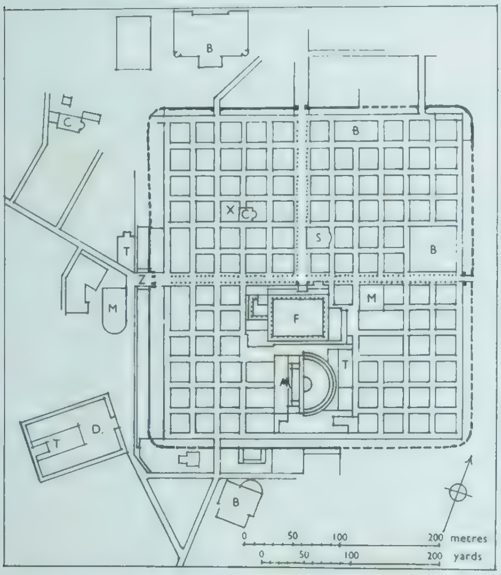

FIGURE 188—*Sketch-plan of Timgad showing at* A, *the theatre; at* B, B, *the* thermae; *at* C, C, *churches; at* D, *the capitol; at* F, *the forum; at* M, M, *market-places; at* S, *the* schola; *at* T, T, *the temples; at* X, *the baptistery; at* Z, *a triumphal arch.*

Palmyra, in Syria, was mostly laid out in the later third century A.D. on the site of an older town, retaining some of the existing buildings. Its chief feature is the magnificent central roadway 3500 ft long and 37 ft wide, flanked on each side by colonnades 16 ft wide. There are ruins of other notable cities of this period in Syria and Jordan—for example, Jerash and Bosra.

In Italy, Aosta, founded as a military colony in 25 B.C., and Turin (figure 194), preserve the original Roman chess-board plan in their older quarters, as do Lucca and Florence to a less degree. Ostia presents some special aspects (figure 189). Lying at the mouth of the Tiber, 15 miles from Rome, it had become the port of Rome, as well as a naval base, by the third century B.C. The original town was planned on conventional military lines. The main road from Rome ran parallel to the river. As the town grew, it was paved with lava and colonnaded. There were, as usual, four gates in the walls, and public buildings round the forum near the centre. The distinctive features of Ostia are the warehouses for grain and other produce, and the large number of commercial offices that occupy many of its *insulae*. Some 70 commercial firms and ship-owners, from all parts of the then known world, had representatives in these offices. Other *insulae* are occupied by shops over which rose blocks of tenements or self-contained flats, some of them several storeys high (vol II, plate 29 A). Here most of the people lived, in contrast to the comparatively low dwellings in the Greek and Roman towns described hitherto. In this respect Ostia resembled Rome, and it contains far more substantial remains of such dwellings than Rome. Its maximum population was about 45 000.

Despite the splendour of its public buildings and its imperial palaces, Rome was never systematically planned (figure 182). Its population in the second century A.D. was between 1¼ and 1½ millions, and its area in the following century was over 3000 acres. It had grown gradually, as the tiny settlement near the ford across the Tiber spread over the seven hills that became famous in history. Thus, though the lay-out of the imperial *fora* and several other parts of the city is a model for posterity, the plan of the ancient city as a whole has little significance for town-planning. As at Athens, most of the area within the lofty city walls was covered with a jumble of mean streets and alleys, with ramshackle tenements many storeys high.

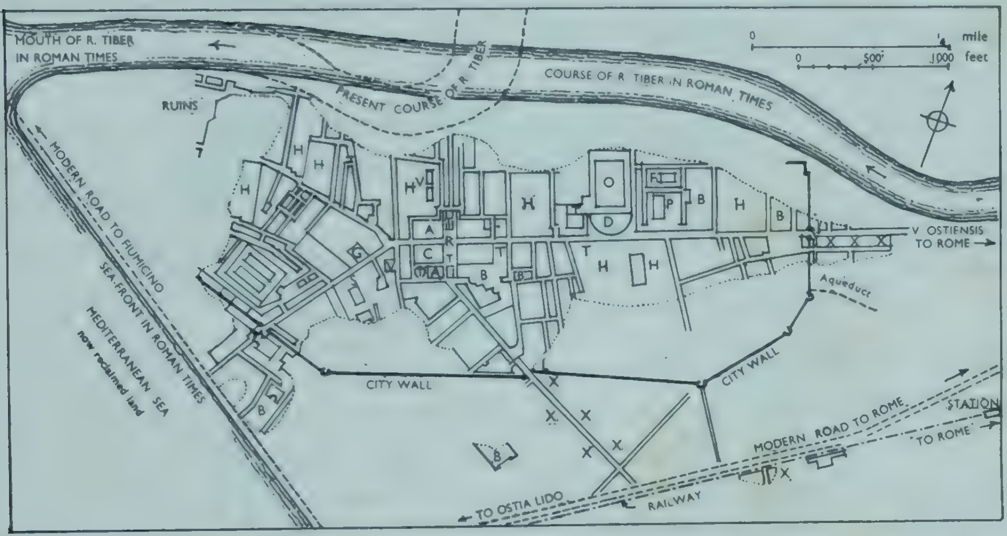

FIGURE 189—*Sketch-plan of Roman Ostia.* (A) *Basilica;* (B) thermae; (C) curia; (D) *theatre;* (F) *firemen's barracks;* (G) *Christian basilica;* (H) *warehouses;* (J) Porta Romana; (L) Porta Laurentina; (M) Porta Marina (*sea-gate*); (O) *commercial offices;* (P) *gymnasium;* (R) *forum;* (S) *school;* (T,T) *temples;* (V) *market-places;* (X) *tombs.*

During the tremendous expansion of the city, the flat marshy land by the river was gradually drained and its streams were enclosed in sewers, of which the *cloaca maxima* still survives. A series of great roads, constructed at an early date, converged upon the city, and the line of some of them was prolonged within the walls (figure 189).

The lavish provision of public baths and other amenities partially mitigated the lack of sanitary arrangements in the tenements, which had no heating-apparatus, no facilities for cooking, and no chimneys. Some of the larger private houses had cesspools. On some of the roads leading out of Rome there were public conveniences at which a small charge was made. At Timgad, the public conveniences near the forum had 20 carved stone seats, each flanked by graceful dolphins, and a neighbouring fountain flushed out the drains. There were also public latrines near the forum at Ostia, entered by a revolving door and provided with marble seats.

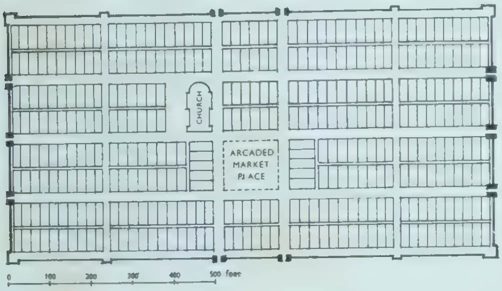

FIGURE 190—*Plan of Monpazier.*

The water-supply of Rome was magnificent (vol II, figure 614). Refuse-disposal appears to have been the perquisite of rag-and-bone men, and there are no references to any municipal scavenging service. Cemeteries were excluded from the city, as from most Roman towns—hence the line of handsome tombs bordering the *Via Appia*, and the numerous catacombs. When the city boundaries were extended to include the Esquiline Hill, an existing cemetery, previously outside the walls, was converted into a public garden and soon became a fashionable resort.

The streets of Rome were unlighted, though there seems to have been a system of communal or municipal lighting at Antioch and Ephesus. The danger of fire in the crowded streets was met, to some extent, by public fire-brigades in continuous attendance at seven fire-stations; but many wealthy private families also maintained private fire-brigades of their own slaves.

IV. THE MIDDLE AGES

Town-planning in its proper sense was largely forgotten or ignored during the thousand years from the fall of Rome to the Renaissance. The growth of towns was fortuitous and spontaneous, not foreseen or regulated. They grew from small villages, or, in some cases, from Roman foundations. Often they clustered round a great church or on the skirts of a fortress.

The need for defence encouraged the crowding of houses and shops within the constricting walls, so that the streets were always narrow; even the market-place was generally congested, and there was no room for gardens. Building by-laws hardly existed. Medieval sanitation is discussed elsewhere (vol II, chs 14, 19).

Despite all this there are some outstanding examples of deliberately planned medieval towns in England and France. The French kings in the thirteenth century established a series of fortified towns (*bastides*) in the newly conquered territory of Languedoc, and their example was followed by leading nobles. Edward I of England (1272–1307), who had received the Duchy of Gascony, laid out some fifty towns in all. Of these, Monpazier in Dordogne (figure 190) is typical. Its plan is monotonously rectangular, the only variations in its oblong housing-units being the spaces for the church and the arcaded market-place, where there was a well. There were ten gates in the enclosing wall. On two sides will be noticed the space within the walls (*pomerium*), represented by streets known as London Wall in London and Back of the Walls at Southampton. Normally this was continued round all the circuit to allow the rapid movement of a garrison. Behind each house in Monpazier was a garden. Another notable example of a French *bastide* is the Lower Town (*La Ville Basse*) at Carcassonne, laid out on chess-board lines by Louis·IX in 1247 to accommodate the inhabitants of the old town which had clustered around the great fortress still known as *La Cité*, their houses having been demolished in order to render the fortress impregnable (figure 191).

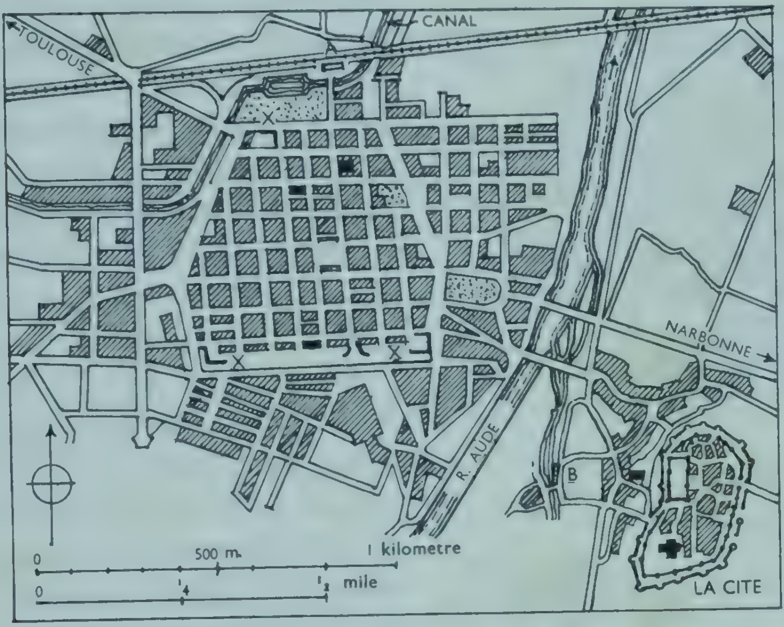

FIGURE 191—*Plan of Carcassonne, the pentagonal shape of the* Ville Basse *being clearly distinguishable. The medieval churches are shown black.* (A) *Railway-station;* (B) Moulin du Roi; (X, X) *remains of medieval fortifications.*

In Britain, Edward I laid out, among other towns, Kingston-upon-Hull, Caernarvon, Conway, and Flint. The most interesting is the little town of Winchelsea in Sussex, replacing an older town subject to inundations from the sea. In 1281 he appointed three commissioners to lay out a new town; one of them had helped to plan his French fortified towns. Part of this scheme still remains (figure 192). Originally it comprised 39 square blocks or *insulae* (including one still occupied by the parish church), but it was never completed. There was a market-place, and the south-east quarter was allotted to the Grey Friars. The whole area was surrounded by a wall with gate-towers, the landward side being also protected by a moat.

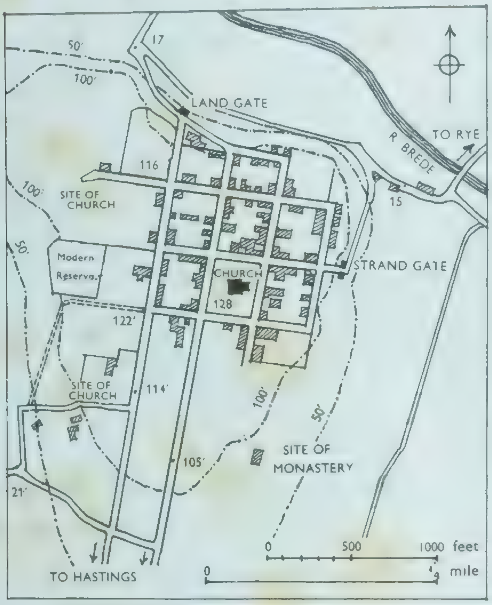

FIGURE 192—*Sketch-plan of Winchelsea. The contour-lines show heights in feet above sea-level.*

Hull was planned in chess-board fashion in 1293 as a port for York, surrounded on the landward side by a ditch. The large parish church stood on one side of the market-place, as at present. In 1296 Edward ordered the citizens of London to select 'four skilful men . . . persons competent to lay out the plans for towns . . . the most able and clever and those who know best how to devise, order and array a new town' to replan Berwick-on-Tweed, which he had just captured and burnt. Twenty-three other cities were ordered to furnish two planners each, making fifty in all. This remarkable commission is often quoted as evidence of the extensive practice of town-planning in England in the thirteenth century: it would be more prudent to conclude from it merely that the king hoped to enlist the help of fifty competent land-surveyors by his nation-wide appeal.

Germany contains a number of picturesque medieval towns, many of which suffered severely during the 1939–45 war. Many of them (such as Rothenburg ob der Tauber, one of the most beautiful and famous) were mere accidental accretions of houses and other buildings in narrow and tortuous streets, usually grouped around a castle or a great church; others were planned solely with a view to defence; others again, such as Cologne, Coblenz, and Regensburg, developed from a Roman rectangular nucleus. In eastern Germany, however, several new towns were systematically founded and definitely planned during the thirteenth century. A typical example is Neubrandenburg (about 85 miles north of Berlin), which was annexed to Mecklenburg in the fourteenth century. This town was definitely planned in 1248 by the Margrave of Brandenburg on a rectilinear system (figure 193), and laid out in approximately equal blocks, one whole block being now occupied by the Marienkirche, another (the market-place) by the eighteenth-century Town Hall and the Duke's own palace, which was erected in 1774–85. Four remarkable brick gate-towers break the circuit of the walls; and indeed Neubrandenburg possesses in these towers and in its churches some of the finest examples of medieval brick architecture in Germany.

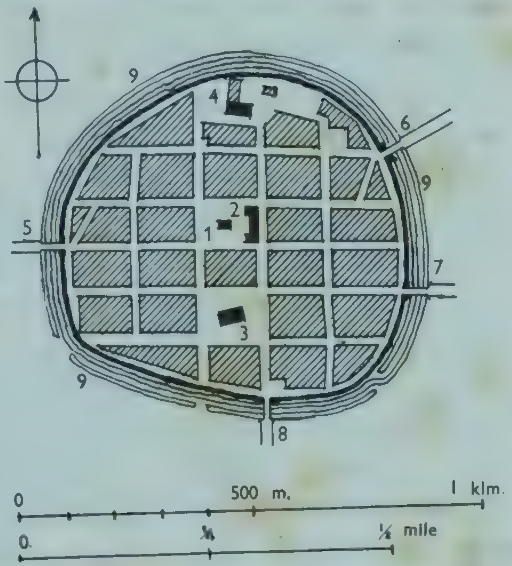

FIGURE 193—*Sketch-plan of Neubrandenburg (with medieval walls drawn in thick line), showing* (1) *the* Rathaus; (2) *the palace;* (3) *the* Marienkirche; (4) *the* Johanneskirche; (5, 6, 7, 8) *gate-towers;* (9) *a dry moat.*

V. THE RENAISSANCE: ITALY

Because the Renaissance originated in Italy, where it made itself felt in architecture during the first half of the fifteenth century, the beginnings of Renaissance town-planning are naturally to be found there too. On the one hand are a number of architects and other writers who developed theories of ideal town-planning in sundry treatises and projects; and on the other is the endeavour to apply such theories in practical examples. Among the theorists, the most notable is that versatile genius Leonardo da Vinci (1452–1519). During his sojourn in Milan from 1481 to 1499 he not only carried out works of military engineering, but made some theoretical study of town-planning. In the 5000 pages of his notebooks there are several memoranda on the subject written between 1483 and 1518.

Some of the notes refer to its aesthetic aspects, treating, for example, 'of cities and other buildings seen in the evening or morning in the mist'; 'of shadows and light on cities'; 'of the smoke of cities'. Others deal with more practical matters, such as 'how to guard against the rush of rivers so that cities may not be struck by them'. One note anticipates a sound rule of modern town-planning: 'let the street be as wide as the universal height of the houses'; another anticipates the modern principle of dispersing the population of overcrowded cities into satellite towns. This memorandum is in the form of an exhortation addressed to Ludovico

Sforza, the ruler of Milan, after the disastrous plagues of 1484–5 in that city, and deserves quotation:

> There will be eternal fame also for the inhabitants of that city built and enlarged by him [the ruler]. . . . There will be ten cities, five thousand houses with thirty thousand inhabitants, and you will separate the great congregation of people who herd together like goats one on top of another, filling every place with foul odour and sowing seeds of pestilence and death. And the city will gain beauty worthy of its name, and it will be useful to you by reason of its revenues, and the eternal fame of its enlargement [4].

Even more striking is his scheme for the reconstruction of a town with traffic on two levels. The high-level streets are for pedestrians, the lower for vehicles. The former are approached by viaducts at the entrances to the town. Flights of steps connect the two levels at frequent intervals. All streets are arcaded, the arcades on the lower level being lighted through openings on the upper level.

Many of Leonardo's notes refer to canals and other waterways inside towns, one sketch showing canals in the place of low-level streets, allowing goods to be delivered from boats to the basement storeys of houses normally entered from the upper level. He gives much attention to irrigation, and is believed to have invented mitred lock-gates (figure 282). 'Nothing is to be thrown into the canals, and every barge is to be obliged to carry away so much mud from the canal, and this is afterwards to be thrown on the bank' [5].

Leonardo was employed on irrigation work at Vigevano in 1494, but there seems to be no evidence that he ever actually planned a town.

About 1500 the Italian architect Francesco di Giorgio Martini published a series of curious ideal designs, all for polygonal fortified towns with streets radiating from a central square to the angles of the polygon. In these schemes, he was more concerned to produce a geometrical pattern of streets than convenient housing-lots. Other ideal designs for heavily fortified polygonal towns with bastions were published by Buonaiuto Lorini at Venice (1592), and by Vincenzo Scamozzi, also at Venice (1615). More interesting than any of these, because it was actually carried out and may still be seen, is the town of Palma Nuova (in Venetia, between Udine and Aquileia), designed in 1593 by Giulio Savorgnan. This small town, now housing between 3000 and 4000 people, had the shape of a nine-pointed star, which it still largely retains.

Turin is an interesting example of a once strongly fortified city deriving from a Roman nucleus (*Augusta Taurinorum*), planned on gridiron lines within a rectangular enclosing wall 2526 by 2320 ft. Even at the end of the sixteenth century, its walls and pattern survived unchanged, save for the addition of bastions and a moat. Three major extensions during the seventeenth century spread its boundaries considerably beyond the Roman nucleus, which the great modern city still incorporates in its plan along with the seventeenth-century additions. The elaborate fortifications have long since been replaced by boulevards and streets (figure 194).

Livorno (Leghorn) is an interesting example of a large city with a polygonal fortified town of the sixteenth century as its nucleus, much of the original pattern of streets and the surrounding moat or canal still surviving.

Rome itself, the most notable example of Renaissance and baroque town-planning in Italy, and perhaps in the whole world, was completely transformed during this period. During the Middle Ages almost all the splendour of the former capital of the Roman world had departed. The population, estimated to have been between 1¼ and 1½ millions in the second century A.D., had sunk to 17 000 while the Popes were resident at Avignon (1309–77). At that period, three-quarters of the area inside the walls was occupied by gardens. Sheep were grazing in the *Forum Romanum* and in the valley between the Palatine and Aventine hills. The people lived mostly in the lower quarters, where the numerous battlemented towers of the nobles rose above crowded hovels and the neglected ruins of antiquity.

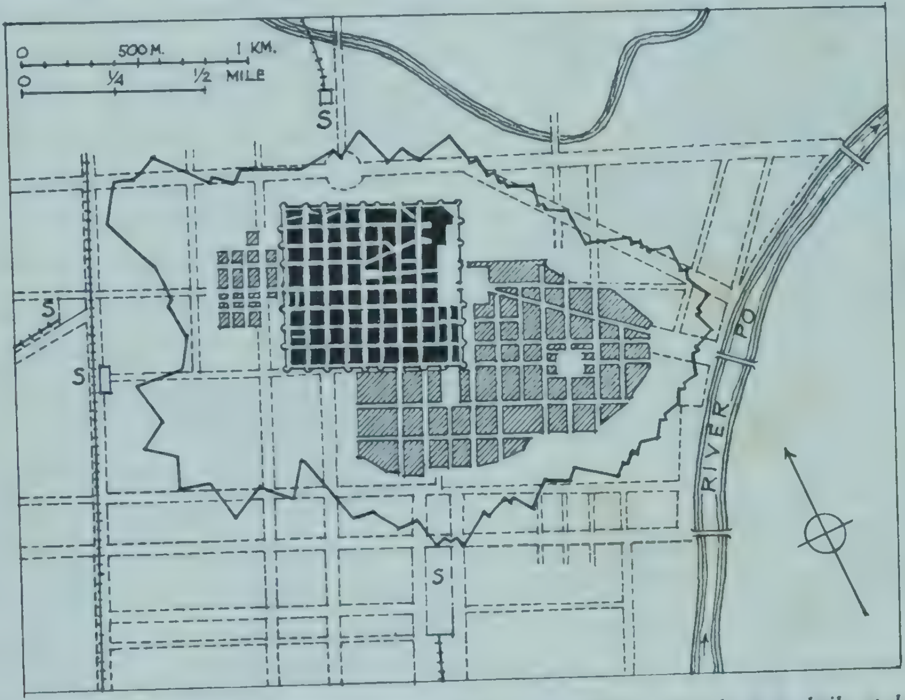

FIGURE 194—*Plan of central Turin, showing the Roman city* (solid black); *the area built up by c 1700* (shaded); *the fortifications at the same date* (black line); *and the principal streets laid out since 1700* (dotted lines). (S, S) *Railway-stations.*

Pope Paul III (1447–64) began the remodelling of the city by straightening the Corso (the ancient *Via Flaminia*) from the church of San Marco to the Arch of Marcus Aurelius, afterwards replaced by the Porta del Popolo. Several leading architects—Bramante, Peruzzi, Sangallo—started to study the historical monuments, and Flavio Biondo wrote his book *Roma Instaurata* in 1444–6. Sixtus IV (1471–84) caused a master-plan of the city to be prepared, and in 1473 built the Ponte Sisto across the Tiber. Alexander VI (1493–1503) replanned the Borgo on the east bank. Julius II (1503–13) laid out the *Via Giulia*. Leo X (1513–21) opened the *Via Leonina*, now the Via di Ripetta (figure 195).

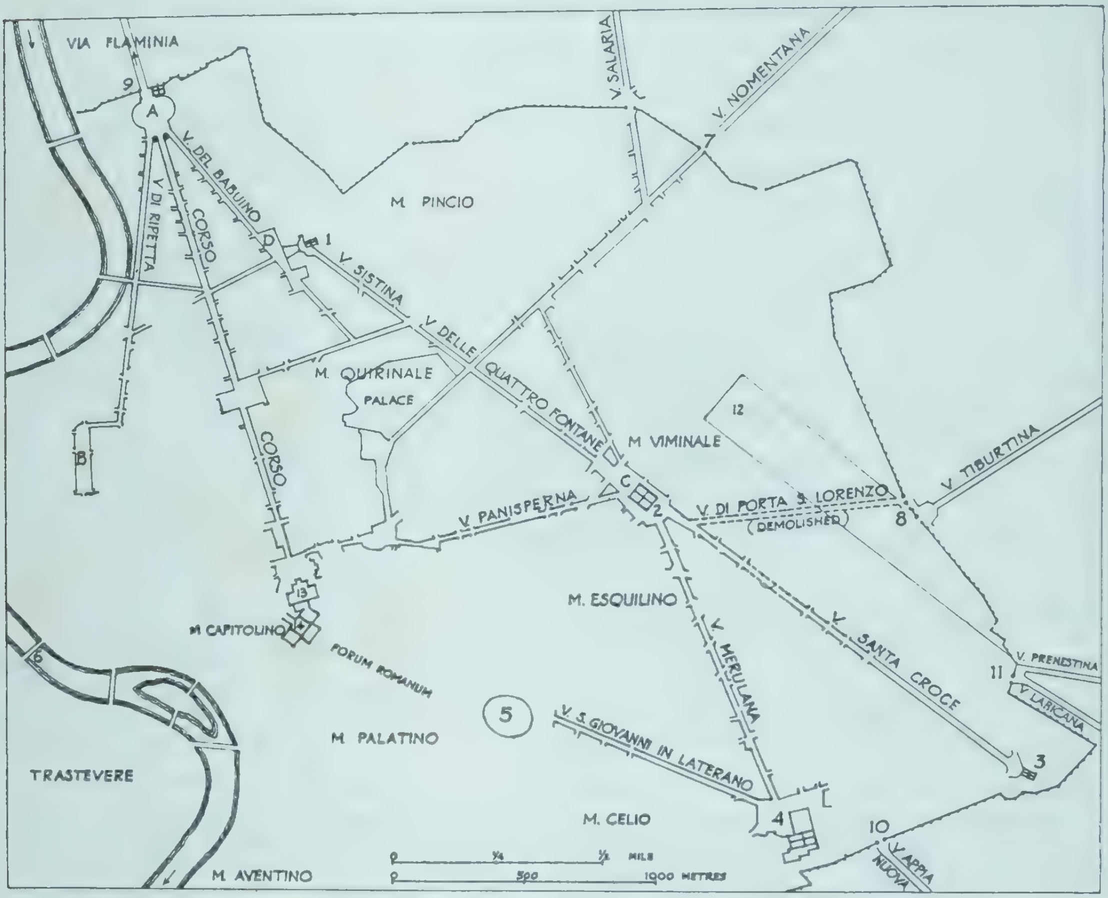

FIGURE 195—*Sketch-plan of central Rome showing streets and buildings mentioned.* (1) *Trinità dei Monti;* (2) *S. Maria Maggiore;* (3) *S. Croce in Gerusalemme;* (4) *S. Giovanni in Laterano;* (5) *Colosseum;* (6) *Ponte Sisto;* (7) *Porta Pia;* (8) *Porta S. Lorenzo;* (9) *Porta del Popolo;* (10) *Porta S. Giovanni;* (11) *Porta Maggiore;* (12) *modern railway-station;* (13) *Vittorio Emmanuele Monument;* (14) *Michelangelo's Piazza, etc.* (A) *Piazza del Popolo;* (B) *Piazza Navona;* (C) *Piazza Esquilina;* (D) *Piazza di Spagna.*

The sack of Rome by the French in 1527 interrupted this work of restoration, which was resumed under Paul IV (1555–9) and Pius IV (1559–66). At this period, the Coelian, Viminal, Esquiline, and Quirinal hills were still completely uninhabited. The principal streets converged on the Ponte Sant' Angelo. The disposition of streets and houses was largely determined by the ancient aqueducts. In 1540 Michelangelo planned the magnificent approach to the Capitol.

Sixtus V (Felice Peretti, 1585–90), with Domenico Fontana as his architect, effected more than any of his predecessors. His major achievement was the layout of the streets converging on the great basilicas of Santa Maria Maggiore and St John Lateran, namely the *Vie Sistina*, *Felice*, *delle Quattro Fontane*, and *di Porta San Lorenzo*. Besides these, he laid out the Lateran and Esquiline piazzas; erected the Lateran Palace; extended the Vatican Palace; and raised obelisks in four of the chief piazzas of the city. Under his rule, the population rose from 45 000 to 100 000, after having previously fallen from 90 000 early in the century to 30 000 after the sack of Rome in 1527.

Sixtus V showed scant respect for historical monuments. He destroyed the *Septizonium* of Severus, but was persuaded to abandon the demolition of the Arco del Velabro and the tomb of Cecilia Metella. His architect Fontana was also most successful in planning the Via del Babuino to balance, on the east of the Corso, the Via di Ripetta which entered the Piazza del Popolo on the west of the Corso, so that a traveller approaching Rome from the north on the old *Via Flaminia* was faced by the three converging streets, the Corso being in the middle and continuing the line of the *Via Flaminia*. One of the two churches that stand symmetrically on either side of this entrance to the Corso had been rebuilt in 1472–7, the other (as we now see it) is a work of the seventeenth century. The whole effect of this lay-out of the Piazza del Popolo is most impressive. The popes of the baroque period from Paul V to Alexander VII (1605–67) were also actively engaged in town-planning as a part of their reconstruction of the Papal City. This phase was dominated by the genius of the architect Lorenzo Bernini, whose work included the great colonnaded piazza of St Peter's and the Piazze Navona, Colonna, and Barberini. Rome contains a number of his graceful fountains as well as many of his larger buildings.

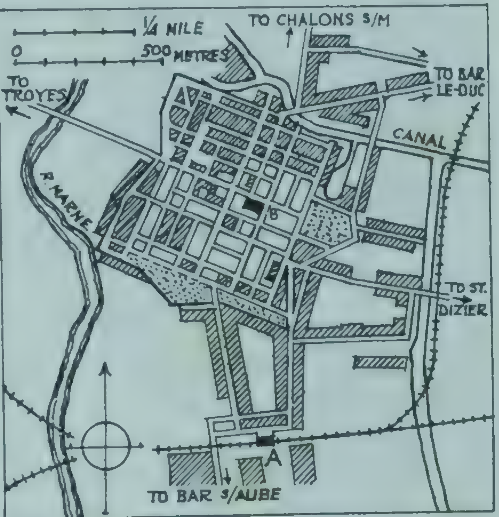

FIGURE 196—*Vitry-le-François. Though the fortifications were demolished in 1891, the original formal lay-out of the town within the line of the polygonal ramparts is clearly seen.* (A) *Railway-station;* (B) *church.*

VI. THE RENAISSANCE: FRANCE

In France a few towns retain the formal rectangular plan on which they were laid out during this period, especially Vitry-le-François, Charleville, Henrichemont, and Richelieu. Much the earliest is Vitry-le-François (Marne), about 20 miles south of Châlons (figure 196). It was originally planned in 1545 by the Bolognese engineer Ieronimo Marino for François I, to replace the neighbouring town of Vitry-en-Perthois, which had been burnt down by Charles V. Although the ramparts were levelled in 1891 and the adjoining marshes drained, the regular lines of the plan of the town can easily be traced. It is obviously derived from Italian models, with the *place d'armes* as the central feature.[1]

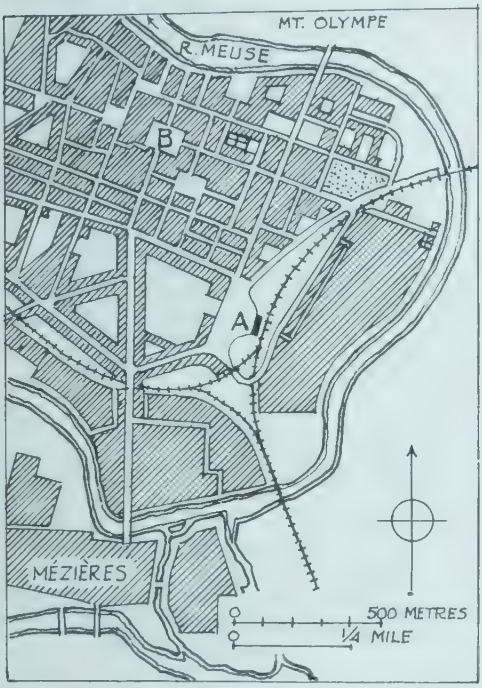

FIGURE 197—*Plan of Charleville, showing formal seventeenth-century lay-out of the old town about the Place Ducale* (B). (A) *Railway-station.*

Meanwhile, Bernard Palissy (1510–90), a potter by trade, who wrote books on gardening and other subjects, devoted some attention to town-planning, advocating 'square and regular planning in every part of the city'. Perret de Chambéry was another writer who concerned himself with the design of imaginary and ideal towns.

The fruits of French and Italian theorizing on this subject are to be seen in three towns laid out during the first third of the seventeenth century. Charleville (Ardennes), a town close to the modern Belgian frontier, derives its name from Charles of Gonzaga, Duke of Mantua and Nevers and Governor of Champagne, who founded it in 1606 (figure 197). It has suffered in many wars. The old fortress on Mont-Olympe across the Meuse was demolished by Louis XIV. The lay-out of the town is strictly formal, the Place Ducale forming the central feature. This is a handsome square surrounded by old houses, with arcades beneath their front walls.

Almost contemporary with Charleville are three of the defensive gateways of Nancy: the Portes de la Craffe (1598), St-Georges, and St-Nicolas; but since much of the fine plan of this city, prepared by an Italian in 1588, was not executed until the eighteenth century, a description of it is omitted here. The small town of Henrichemont, about 20 miles north-west of Bourges (Cher) was founded by Sully in 1609. Its lay-out is a combination of the radiating with the rectangular plan.

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[1] Vitry-le-François was largely destroyed in the war of 1939–45. It has now been rebuilt on the old plan.

The model town of Richelieu (Indre-et-Loire), founded by the famous cardinal, was designed by the architect Jacques Lemercier (1585–1654) and laid out between 1631 and 1638 as an appendage to the magnificent château which the cardinal had begun to build in 1620 when he was only 35 years of age. The marshy site was drained by canalizing the little river Mable (figure 198) and diverting it to serve moats surrounding the château and the town. Two thousand men were employed to build the château, which was completed in 1635. Since its decay in the eighteenth century only a single pavilion, known as the *Dôme*, and two small isolated farm-buildings remain, with the foundations of the great mansion and its surrounding moat. John Evelyn recorded his impressions of the château and the adjoining model town, of which he wrote:

> The Towne is built in a low, marshy-ground, having a small river cutt by hand, very even and straite, capable of bringing up a small vessell. It consists of one onely considerable streete, the houses on both sides (as indeede they are throughout the towne), built most exactly uniforme, after a modern handsome designe. It has a large goodly Market-house and Place, opposite to which [is] the Church built all of free-stone. . . . It being onely the name of the place, and an old house there standing, & belonging to his ancestors, which allurd him to build. This pretty town is also handsomely wall'd about & moated, with a kind of slight fortification, two fayre-gates & drawbridges. Before the gate towards the Palace is a most spacious circle, where the faire is annualy kept [6].

Evelyn's words are still faithfully descriptive of the town as it stands today, a rare and even unique example of Renaissance town-planning. The twenty-eight principal houses in its Grande Rue were earmarked from the outset for the chief officials of the cardinal's immense retinue, and some of the lesser dwellings were intended to accommodate others of his household, but the town was never meant to be restricted to his own employees, and indeed he offered inducements to attract others there. The citizens were excused all taxes until 100 houses had been built, and thereafter were granted a special remission; but the freeholders had to use Lemercier's standard designs, and buildings had to be completed within a stipulated period. It has been estimated that the maximum population in the seventeenth century must have been 5000 to 6000; it is now about 1800.

The Grande Rue, running north and south and crossed by transverse streets, is interrupted by the Place du Marché and the Place des Réligieuses, as originally planned. The whole town measures about 600 by 400 yds. It is surrounded by a

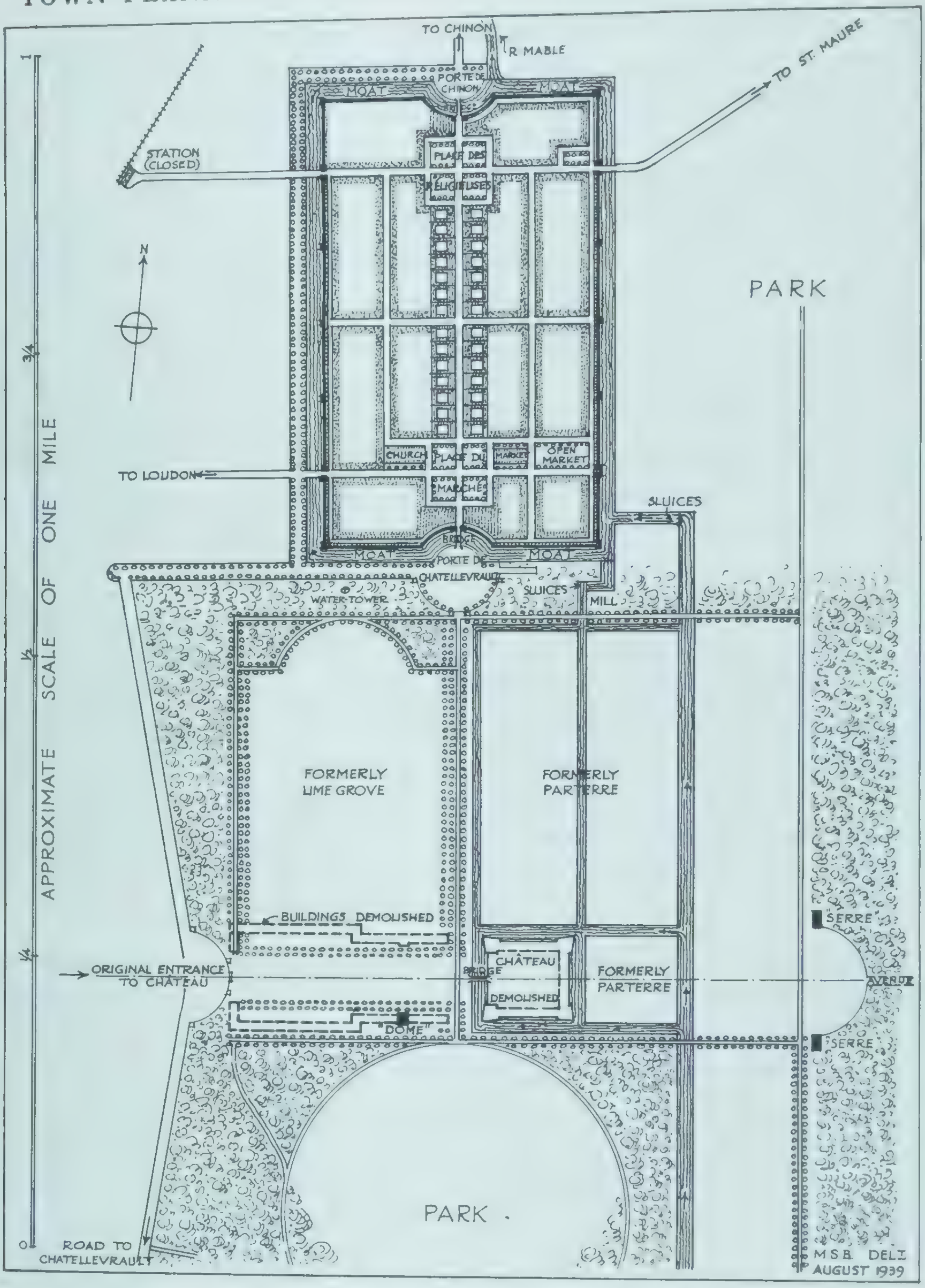

FIGURE 198—*Sketch-plan of the town and château of Richelieu.*

high stone wall with several gateways, by a moat about 70 ft wide and originally 10 ft deep (now filled in), and by enclosing avenues, of which about half remain. The width of the Grande Rue is about 37 ft, that of the other streets 20 ft or less. The church stands unaltered. The market-hall, opposite the church, is a fine example of carpentry, the main posts of the nave (which is about 28 ft wide) measuring 15 by 12 in. The principal houses in the Grande Rue stand almost unchanged, save for the insertion of a shop-front here and there. They are of brickwork, now covered with stucco, with fine limestone dressings. The frontage of each is about 70 ft, the depth from front to back about 30 ft, with a courtyard in the rear and a spacious walled garden behind it.

A good deal of town-planning and town-improvement was also carried out in Paris during the seventeenth century. Henri IV (1589–1610) was the first European ruler since Roman days to undertake building operations on a large scale for political and social reasons, including the provision of employment. Paris in 1600 was in a deplorable state—ill planned, overcrowded, and insanitary. It could boast of but two bridges across the Seine, and five insignificant squares. In 1600, and again in 1608, Henri issued ordinances for the widening, alignment, and paving of streets, forbidding overhanging storeys. In 1600, the triangular Place Dauphine was laid out with middle-class houses and shops, incorporating two islets in the site. In 1604 the unfinished Pont Neuf was completed, and the Place du Pont Neuf followed soon afterwards. The charming Place Royale, now the Place des Vosges, still remains—a square garden surrounded by aristocratic houses with a continuous arcade beneath their façades. A splendid scheme for a Porte and Place de France on the north of the city [7] was prepared under the king's personal supervision, but was abandoned after his death.

His successor, Louis XIII, in 1635 laid out the Île-Saint-Louis, hitherto occupied by meadows and gardens. The scheme consisted of fine houses and streets arranged on a gridiron pattern. Under Louis XIV, the Portes St-Denis (1672) and St-Martin (1674) were erected, the circular Place des Victoires (1684–6) and the Place Louis-le-Grand, now the Place Vendôme, were laid out to the glory of the king, and the Quai Malaquais (1670) was constructed. In 1676, Louis ordered the city architect, Pierre Bullet (1639–1716), to prepare a complete plan of Paris, showing not only existing streets and buildings, but also new works in progress or projected.

VII. THE BUILDING OF AMSTERDAM

One of the most remarkable examples of historical town-planning is the inner, and older, part of the city of Amsterdam (figure 199). The name explains the situation and origin of the city, for it recalls the construction of a castle and a dam on the little river Amstel in 1204, at the point where that stream flows into the Ij or Y, an inlet of the Zuider Zee. At the same time a sea-dike was built to prevent inundation from the Ij. The first houses were erected east of the Amstel, then others followed on the west bank. The earliest defensive ditches (*Voorburgwallen*) were dug outside the new settlement in 1342 and were connected with the Amstel and the Ij by sluices. The western ditch was filled in the nineteenth century, but the street which has replaced it is still called the Nieuwezijde Voorburgwal. A second line of ditches about 60 yd outside the *Voorburgwallen*, and known as the Singel (girdle), was dug in 1383, and was similarly controlled by sluices. Houses were then erected along the canals, on timber piles about 40 ft long. Further extensions followed in 1442, monasteries were established, ship-building and other industries appeared, and in 1481–2 the town was fortified with towers for the first time. One of these, the Schreijerstoren, remains.

In 1593 a more elaborate system of bastions was constructed, and a barrage was erected in the Ij to protect merchant-shipping. In 1610 began the remarkable and ambitious scheme of concentric extension which, in quadrupling the habitable area, produced Amsterdam's unique plan. The new bastions completed in 1593 were demolished, a new canal (Heerengracht) replaced them, and two more canals (Keizersgracht and Prinsengracht) were dug parallel to it. A fourth canal (Singelgracht, 1658, 6½ miles long) surrounded these three, with a new line of bastions. Small radial canals crossing the main concentric canals created a spider's-web pattern. The planning of the outermost ring, between the Singelgracht and the Prinsengracht, was not, however, strictly radial. Except for an area reserved for artisan dwellings on the west, all the canals were lined with trees and with the handsome houses of the wealthier people. A park, the Plantage (since built over), was provided on the north-east; but, except for this public open space, the whole area was filled with houses by 1667. The building of houses was left to private enterprise, though the general lay-out and the canal-construction were done by the municipality. During the seventeenth century, part of the 'Dam' was filled in, and the town hall (now the royal palace) was erected on the site in 1648–55, based on a foundation of 13 659 piles. With the possible exception of Venice, and some modern cities of the east, Amsterdam must surely be built on one of the worst sites in the world. Beneath a top layer of mud, about 50 ft thick, is a belt of sand 10 ft thick, into which the long oak piles had to be driven. The canals divide the old town into nearly 100 islands, crossed by about 300 bridges.

The outer fortifications of Amsterdam were demolished in the third quarter of the nineteenth century, and the ground along the Singelgracht was laid out with gardens. Some of the later alterations to the city are shown in dotted lines on figure 199. Its population had grown from an estimated 50 000 in 1600 to about a quarter of a million in 1859 (nearly all of whom were contained within the fortifications), and numbers over 860 000 at the present day, spread over a much wider area.

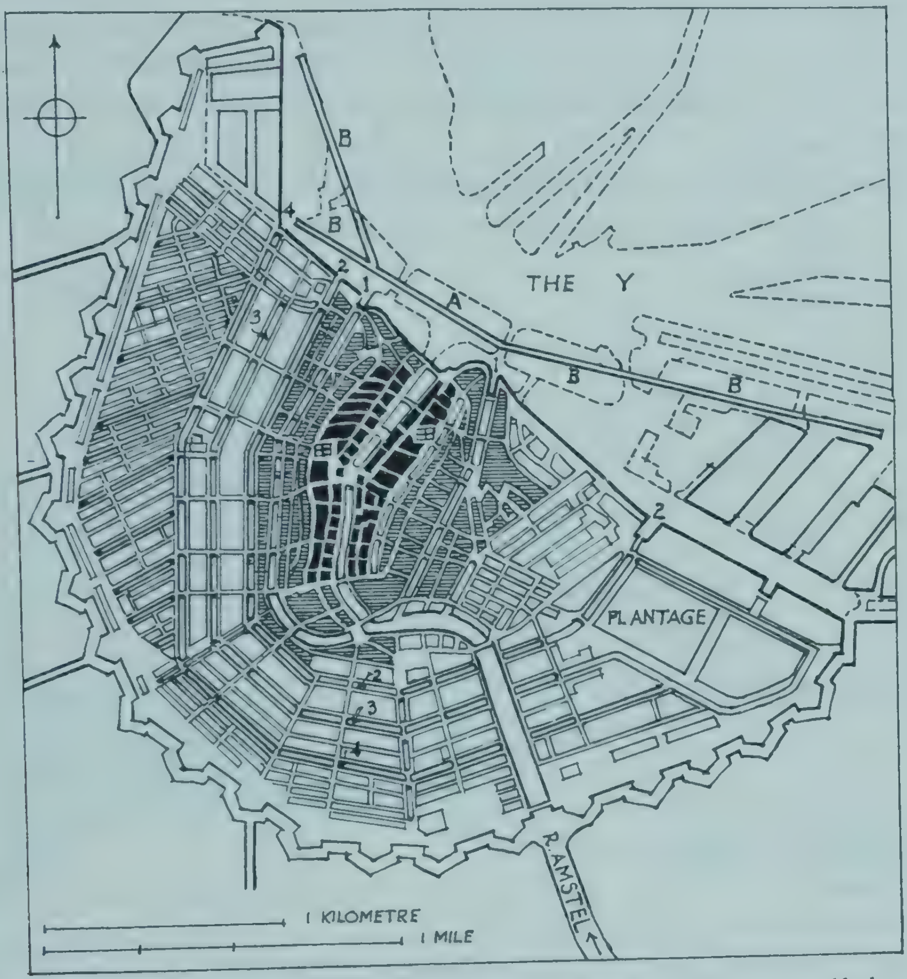

FIGURE 199—*Amsterdam c 1670, showing the stages of the city's growth. The area in black represents the city c 1400; the area horizontally shaded was built between 1400 and 1600; the remaining streets within the fortifications were built between 1600 and 1670 according to a plan prepared in 1612.* (B) *Breakwater or mole, since demolished. Canals:* (1) *Singel;* (2) *Heerengracht;* (3) *Keizersgracht;* (4) *Prinsengracht. The dotted line shows the modern foreshore, docks, etc.* (A) *Central railway-station.*

VIII. THE PLANNING OF LONDON AFTER THE GREAT FIRE

Before the Great Fire of London in 1666 there is little evidence of any conscious town-planning in England. Repeated efforts were indeed made by Elizabeth I and James I to restrict the uncontrolled spread of London beyond the old city walls, and some ordinances were made to regulate the construction of buildings; but the first attempts at formal town-planning were due to the architect Inigo Jones, who had studied in Italy (p 256). In 1618 he laid out Lincoln's Inn Fields with a large open square surrounded by handsome houses, some of which were completed in 1638–9. Two sides of the square were finished by 1641, a third side by 1659, and the fourth a few years later. In 1631 he began to lay out Covent Garden and adjoining streets for the Duke of Bedford, with a central open space, in which sheds for a market were erected in 1632, surrounded by houses standing on arcades, and with St Paul's Church (since rebuilt in its original form) as a principal feature.

The development of Leicester Square (formerly Leicester Fields) began when the Earl of Leicester built his own houses about 1631, but the remainder of the scheme was not completed until after the Restoration in 1660. Bloomsbury Square and St James's Square were both begun in or about 1664. Meanwhile, schemes for building an embankment or quay along the Thames and for embanking the Fleet Ditch had been discussed; while John Evelyn, after his travels abroad, urged the need for replanning London in his treatise on smoke abatement, *Fumifugium* (1661). This was the position when the Great Fire, which broke out on 2 September 1666 and raged for five or six days, destroyed the greater part of the City of London, and opened a new chapter in the history of English town-planning by affording an opportunity such as had never occurred before (figure 200).

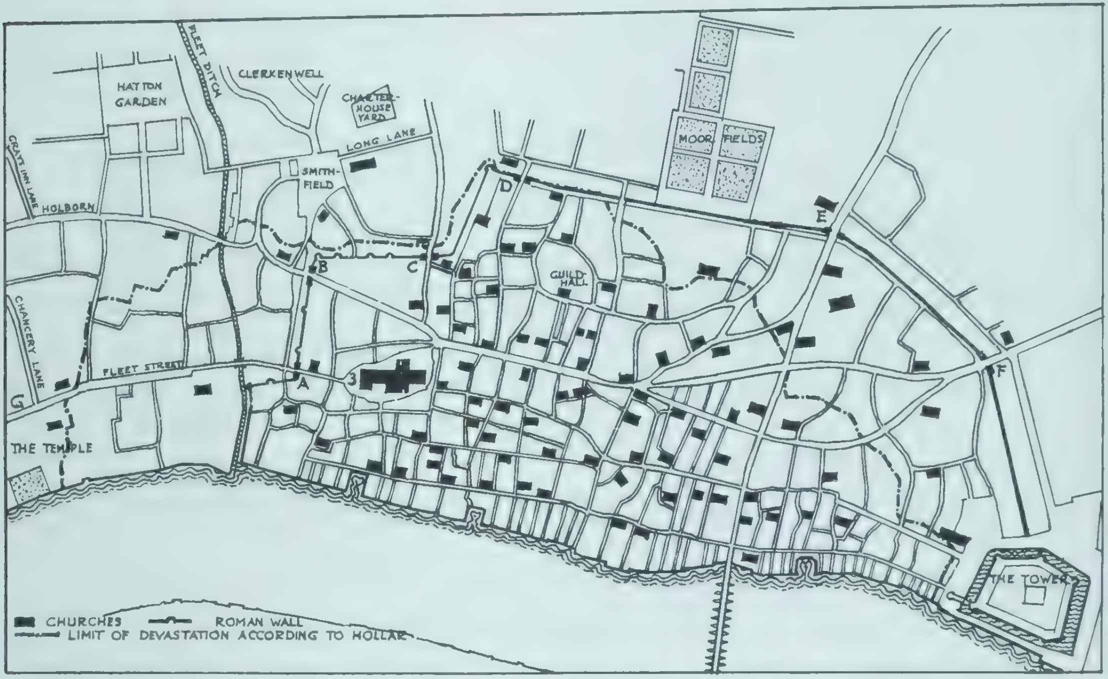

FIGURE 200—*Plan of the City of London, prepared from a survey of the ruins after the fire in December 1666 by order of the City authorities.* (A) *Ludgate;* (B) *Newgate;* (C) *Aldersgate;* (D) *Cripplegate;* (E) *Bishopsgate;* (F) *Aldgate;* (G) *Temple Bar;* (3) *St Paul's Cathedral.*

The story of the course and results of the Fire may be read in the narratives of Evelyn and Pepys; the ruins were still smouldering when the former virtuoso, with amazing enterprise, submitted to Charles II a plan for rebuilding based upon a hurried personal survey of the City. His diary for 13 September 1666 describes an interview with the king in 'the Queen's bedchamber, her Majesty and the Duke [of York] onely being present', when Evelyn explained his plan to them. 'But Dr Wren had got the start of me. Both of us did coincide so frequently, that his Majestie was not displeas'd with it, & it caused divers alterations; and truly there was never a more glorious Phoenix upon earth, if it do at last emerge out of these cinders, & as the design is layd, with the present fervour of the undertakers.'

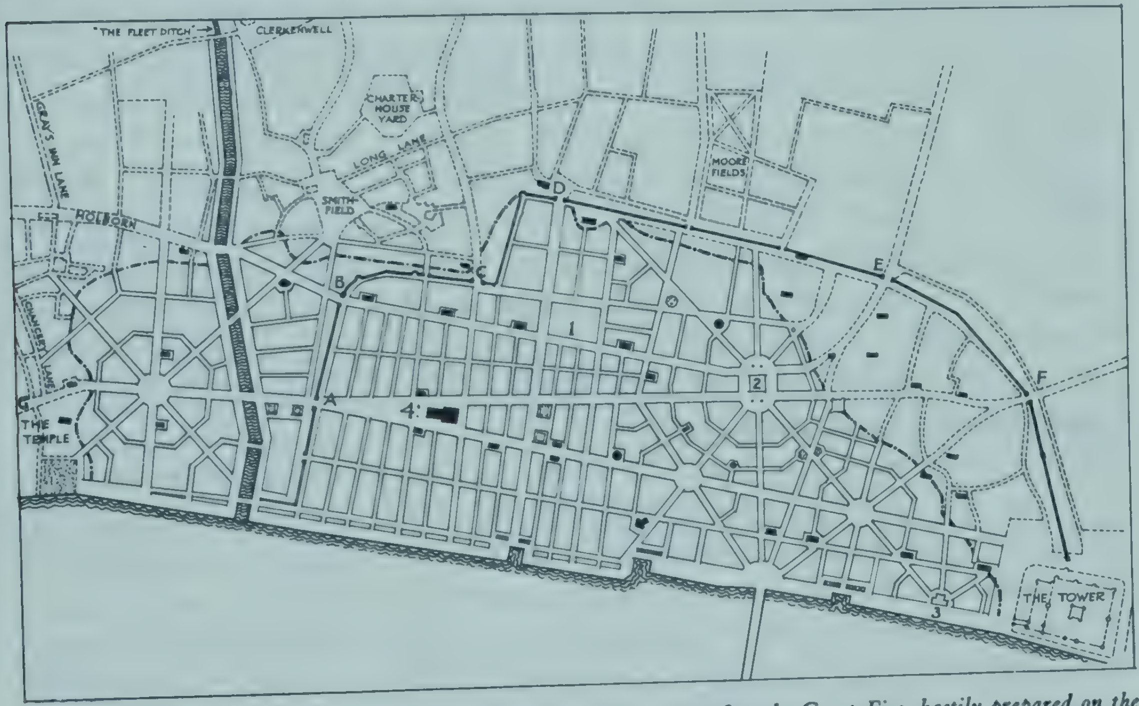

FIGURE 201—*Wren's plan for the rebuilding of the City of London after the Great Fire, hastily prepared on the basis of a rough survey.* (A) *Ludgate;* (B) *Newgate;* (C) *Aldersgate;* (D) *Cripplegate;* (E) *Bishopsgate;* (F) *Aldgate;* (G) *Temple Bar;* (1) *Guildhall;* (2) *Royal Exchange;* (3) *Customs House;* (4) *St Paul's Cathedral.*

At that time, Wren's career as an architect was only two or three years old, but he had already been consulted about the restoration of Old St Paul's, on the strength of his great scientific attainments. The king's first action after the interview on 13 September was to appoint three Crown commissioners (Wren among them) to organize the rebuilding of London in collaboration with three representatives of the City, including Robert Hooke and Peter Mills. Hooke (p 257) also submitted a plan for rebuilding, as did Mills (whose plan has been lost) and two other persons, one of whom furnished two alternative schemes. Of seven plans in all, six have survived, and of these the designs of Wren and Evelyn are the most skilful as well as the best known (figure 201).

As Evelyn observed, there were many points of similarity between his plan and Wren's. Both showed embankments on either side of a widened and straightened Fleet River. Both treated St Paul's Cathedral (the medieval building) as a focal point at the end of converging street vistas. Both provided a great piazza in Fleet Street half-way between Fleet Bridge (on the site of the modern Ludgate Circus) and Temple Bar. Wren proposed a wide continuous riverside quay from the Tower of London to the Temple; Evelyn offered a range of public buildings facing the river, with a street behind them. He moved the Royal Exchange to the river, whereas Wren left it on its original site and made it a feature of his lay-out. Both plans showed a number of diagonal streets, though differently arranged. Wren's scheme included wide straight streets from Fleet Bridge by way of St Paul's to Aldgate, from St Paul's to Tower Hill, and from Queenhithe to Moorgate. Both designs took account of the numerous parish churches. Of the two plans, Wren's was the more practical, Evelyn's the more idealistic and geometrical; but both displayed some acquaintance with continental town-planning principles.

Either plan would have vastly benefited the City of London, yet neither of them, nor any one of those submitted, was ever carried out. There were lengthy arguments in the House of Commons; but in the end the enormous cost and the legal difficulties involved in settling claims of ownership and compensation, amounting to many thousands, together with the frantic anxiety of shopkeepers and others to resume business at once on their old sites, proved too much for the authorities. All the proposals were abandoned, and the only result of this memorable contest of talent was the canalizing of the foul Fleet Ditch or Fleet River from the Thames up to Holborn Bridge (on the site of Holborn Viaduct) in 1671–4, carried out by Hooke as City surveyor; but that attractive improvement, with its quays, has long been buried underground beneath New Bridge Street and Farringdon Street.

During the last few years of the seventeenth century, several more fine squares were laid out in London, namely Golden Square (1688–1700), Grosvenor Square (1695), Berkeley Square (1698), Red Lion Square (1698), and Kensington Square (1698).

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12

LAND DRAINAGE AND RECLAMATION

L. E. HARRIS

LAND-RECLAMATION comprises essentially the improvement of land for agricultural and other purposes. It involves specific methods of (*a*) embanking submerged shore-lands from the sea, (*b*) training and regulating rivers to prevent flooding, from which arise (*c*) the draining of low-lying lands and marshes, and, at the other extreme, (*d*) the irrigation of arid wastes. With this last, however, we are not concerned here. Our survey is confined to four main European countries, the Netherlands, Italy, France, and England, where there was no extensive irrigation in the sixteenth and seventeenth centuries, and where it is still not practised significantly. But each of these four countries has had its special methods and principles of land-reclamation, characteristic both technologically and historically, and in all of them the sixteenth and seventeenth centuries brought rapid developments, on which their present systems of drainage are founded.

I. THE NETHERLANDS

The real originators of land-reclamation in northern Europe, of sea-defences and polder-formation—or what might be termed assisted accretion—were the Netherlanders, from motives forced upon them largely by self-preservation. The skill which they thus acquired was utilized by other countries certainly as far back as the end of the tenth century when, for example, the bishops of Bremen, the marquises of Brandenburg, and others had employed the coastal Frisians on such works (vol II, p 683). But it is important to note that in this statement we confine ourselves to northern Europe, excluding particularly Italy where, as will be seen later, the influence of the Netherlands, even if to some degree existing, was far from predominant (p 309).

By the beginning of the sixteenth century the Netherlands possessed a well developed system of land-reclamation based on the very early habitations on the *terpen* or clay islands which remained above water in the coastal areas where, thousands of years ago, the sea had broken through the sand-dunes then forming a natural protection on the coast line (vol II, pp 681–5). The primitive but systematic building of embankments and artificial protective works originated some time before the eleventh century, but there is doubt whether the early dike construction was undertaken primarily as a means of protecting existing lands from floods, or as a means of land-reclamation: whether, therefore, it was of a defensive or an offensive character. By the opening of the sixteenth century this comparatively primitive construction had developed into regulated designs, differing in type to suit regional conditions. Thus in west Friesland, where the dikes had to withstand the waves of the open sea, it was found essential to protect the face of the dike by some means. In the calmer estuarine waters of Zeeland the need for protection was not so great. Furthermore, the clay available in Zeeland was much more suited to dike-building than that of Friesland, so that while in Zeeland simple protection by grass and seaweed was sufficient, more substantial materials were called for in Friesland.

The simple making of an embankment with masses of boulder-clay was almost instinctive, but the technique of protecting the face of the embankment or dike could be learnt only from practical experience, often bitter as the sea flooded through breaches. Thus there developed the various forms of dikes:

(i) the *slikkerdijk*, with an earth core, the slopes plastered with clay, later augmented by layers of straw bundles, or bundles of osiers;
(ii) the *wierdijk*, in which seaweed replaced the straw or osiers; and
(iii) the *rietdijk*, where bundles of reeds replaced the seaweed (vol II, pp. 684–6).

Later, in the fifteenth century, more substantial methods of protection were devised, such as the palisade of piles, and later still, towards the end of the sixteenth century, the *krebbingen*, consisting of two rows of short piles a few feet apart, the space between being filled with faggots or fascines held down by straw (figure 208). By the end of the sixteenth century stone pitching had been used experimentally, but this protection was in general found to be too expensive.

About 1578 Andries Vierlingh, a native of Brabant, wrote an important general work on dike-building, which remained unpublished until 1920, when it was given the title *Tractaet van dyckagie* [1]. Vierlingh was for many years bailiff of Steenbergen (Brabant), and in this post he had much concern with drainage and the embanking of polders, while in his youth, in 1530, he had assisted in the work of closing gaps in the harbour-dike at Middelburg, and later in land-reclamation in Zuid Beveland. In 1552 he was dike-master of the Graff-Hendriks polder at Steenbergen, and had considerable experience of such work not only in Brabant but also in Zeeland, South Holland, and west Friesland. The importance of Vierlingh's treatise lies in the fact that here we have for the first time a codification of methods employed in the sixteenth century principally for the construction of dikes, but also for the building of flood-gates and the like. The work is in three books, and Vierlingh had indeed planned the fourth and fifth books in which he intended to deal with the control of rivers and the deepening of harbours, and to treat of the general subject of inundations. His work, therefore, gives us a picture of hydraulic practices before any true science of hydraulics existed. Furthermore, the *Tractaet* demonstrates that comparatively advanced methods of dike-construction and protection were already in use and, indeed, were not very different from those in use today. A close examination of Vierlingh's book, particularly in relation to Brabant, shows that, as compared with the land reclaimed inside the old sea-dikes before the end of the fifteenth century, there had been very considerable expansion by Vierlingh's time, when the new dikes were up to, or even in some cases beyond, the present-day limits. It was also at this period that intense activity began in another direction, the 'laying dry' of inland 'meers' or lakes.

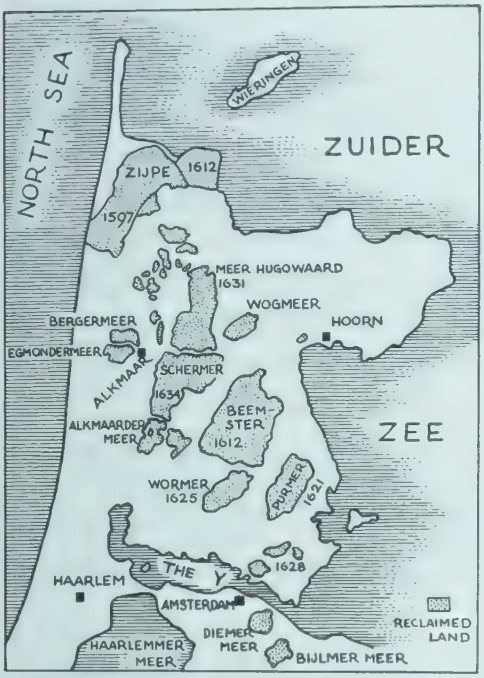

FIGURE 202—*North Holland, showing progress in* droogmakerij *during the sixteenth and seventeenth centuries.*

This 'laying dry' (*droogmakerij*), a new technique essentially different from that of embanking from the sea, started slowly and tentatively in the early years of the sixteenth century. Thus between 1542 and 1548 the Dergmeer, the Kerkmeer, the Kromwater, the Weidgreb, and the Rietgreb, all small meers in the northern part of the Netherlands, were drained and turned into valuable agricultural land (figure 202). Then in 1556 the Count Van Egmond began the greater undertaking of draining the Egmondermeer, quickly followed by, among others, Hendrik Van Brederode in the Bergermeer, and Johann Van Oldenbarnevelt in the Dieps and Tjaalingermeer. The initiative for all this work came from the various 'adventurers' and undertakers, to whom the ultimate agricultural value of the land was of less importance than their immediate profit on their capital adventured. To give some idea of the growth of this *droogmakerij* between 1540 and 1565, the total area of land reclaimed in North and South Holland, Friesland, Groningen, Zeeland, and north Brabant was 35 608 hectares, of which only 1349 hectares were drained meers, the rest having been obtained by diking from the sea. Between 1615 and 1640 the total was 25 513 hectares, of which no fewer than 19 060 were obtained by the 'laying dry' of meers. The method of reclaiming these drowned lands was to surround the whole area with a strong bank, or *ringdijk*, the earth for which was dug from the outer foot of the dike, so forming a channel, or *ringvaart*. When the *ringdijk* and *ringvaart* were completed then the drainage-mills, generally sited on the *ringdijk*, began their work of pumping out the water from the meer into the *ringvaart*, whence it flowed by gravity, through sluices if necessary, to the river or main canal (figure 206).

Beyond their agricultural importance these *droogmakerijen* have an added significance in the impetus that they gave to the technical development of the drainage-mill. This, the windmill-driven scoop-wheel, was not the child of meer-drainage. It had, indeed, come into use in a somewhat primitive form towards the end of the fourteenth century, much later than wind-driven corn-mills, but its use as a drainage machine could never have been practically successful without the invention about the middle of the fifteenth century of the rotating cap, which enabled the sails to be turned into the eye of the wind without turning the body of the mill, an impossibility with a fixed scoop-wheel.[1] But for this invention the drainage of meers and other low-lying grounds in Holland, formed by natural shrinkage of the land and by the creation of vast flooded pits from which peat had been dug for fuel, might have been indefinitely delayed. Between 1560 and 1700 as many as 102 patents for drainage-mills were granted by the States-General and individual states, besides numerous patents for other forms of pumps such as screw-pumps, spiral pumps, and the like. Not all these were capable of working, but the figures give some idea of the importance of the problem of water-raising in relation to land-reclamation. Furthermore, the drainage-mill introduces two outstanding names in the history of land reclamation in the Netherlands: Simon Stevin (1548–1620) and Jan Adriaanszoon Leeghwater (1575–1650), both of whom were responsible for important developments in the design and construction of drainage-mills.

Stevin's claim to fame rests on a much wider basis for he was, like his contemporary Galileo Galilei, not only an accomplished mathematician but a combination of what we should term today a scientist and a practical hydraulic engineer, with the emphasis on elementary hydrostatics rather than hydrodynamics. Stevin, who was born at Bruges, entered the university of Leiden in 1583, and was later employed as an engineer in the army of Prince Maurice. Probably he was responsible for, or adviser on, the construction of the Prinsendijk on the west side of the Grote Wiericke channel, which formed part of the water-defences of the province of Holland in the Spanish war. The first of Stevin's patents was granted to him by the States of Holland in 1584. It covered three inventions: (i) to bring all sorts of ships across shallow waters; (ii) to bring ships across dams; and (iii) to raise water by other means than so far used (to drain polders, harbours, and so forth). Only the last of these concerns us, and this device, according to his son Hendrik Stevin (1613–70), was a special type of piston-pump which, however, was never adopted widely for polder drainage; indeed, a pump of this type is fundamentally unsuited to such work.

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[1] In this cap-mill (*wipmolen*) the drive was transmitted to the scoop-wheel by a shaft running through the hollow post supporting the body of the mill (vol II, p 625).

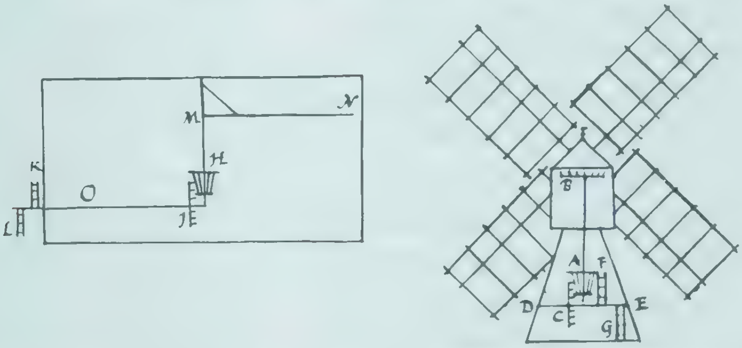

Figure 203—*An original drawing by Simon Stevin of the drainage-mills described in his patent of 28 November 1589.* (Left) *Horse-mill driving scoop-wheel through right-angle gears;* (right) *turret-mill driving scoop-wheel.*

In 1588 the States-General, through the Earl of Leicester, granted Stevin a patent for a 'drainage mill of high capacity' which, again according to Hendrik Stevin, included a scoop-wheel with only six blades as opposed to the usual 20 or 24, each blade being provided with leather strips sliding along the floor and sides of the wheel-race (figure 203). That this device was successful appears from a series of testimonials drawn up in the years 1590 and 1591 relating to mills of this type built by Stevin at, among other places, the Duyvelsgat at Delft and the Stolwijksche sluice at Souderak, where it was stated that the new mill 'in one hour lifted as much water as the said Beÿer Mill in three hours'. Stevin himself wrote to the bailiff and burgomaster of Delft and showed mathematically that his new drainage-mill there lifted four times as much water as the old mill did. It has been suggested that Stevin's invention was not adopted widely because the Archimedean screw, with or without a fixed casing, was then largely ousting the scoop-wheel. A more likely explanation is that, although the leather strips and reduced number of blades might give a higher hydraulic efficiency, principally by reducing blade-tip leakage, the leather strips must have required frequent and costly replacement. The standard design of scoop-wheel cost little to maintain, and in the larger drainage-mills it outlasted the competition from Archimedean screws, spiral pumps, and other devices introduced into the Netherlands in the sixteenth and seventeenth centuries. But the Archimedean pump for which Dominicus van Melckenbeke of Middelburg was granted a patent in 1598 found many applications in the *tjaskers*, or small inclined windmills, particularly in the north-eastern part of the country (figure 204). The logical evolution from the Archimedean screw, the screw with the fixed casing, was the subject of a patent granted to Symon Hulsbos of Leiden in 1634.

Stevin's fame in relation to drainage-mills is firmly based on his treatise *Van de molens* ('On Mills') in which he supports his practical developments by original theoretical studies in statics and hydrostatics [2]. Indeed, this book has claims to be the oldest on the subject, anticipating Smeaton's researches by some 150 years. And if Vierlingh's *Tractaet van dyckagie* is the oldest codified work on embankments in general, the first two chapters of Stevin's *Nieuwe maniere van sterctebou, door spilsluysen* ('New manner of Fortification by Sluices'), published in 1617, are, perhaps, the oldest printed treatise on sluices extant in Europe [3].

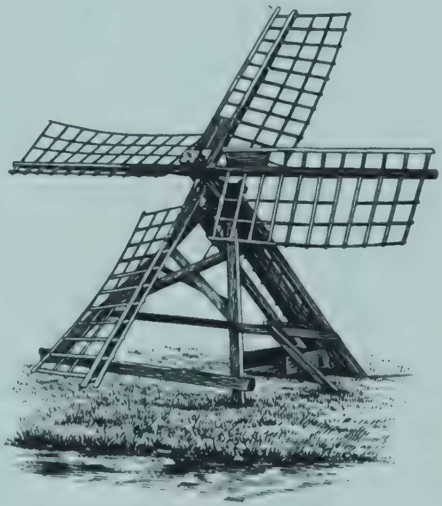

FIGURE 204—*A* tjasker *mill, Friesland.*

Jan Adriaanszoon, who in later years adopted the surname of Leeghwater, was a very different type of man from Simon Stevin. A self-made man, he was born in 1575 at a village north of Amsterdam, the son of a carpenter who built the first sluice there in 1594. If, as previously suggested, the development of the drainage-mill was hastened by the expansion of the *droogmakerij*, it is no less true to say that the same factor contributed largely to the creation of Leeghwater, because although he became well known as an hydraulic engineer of wide experience in the planning of drainage-canals, the construction of sluices, and so on, his lasting reputation stands firmly on his skill as the *Molenmaker en Ingenieur van de Rijp* ('Millwright and Engineer of de Rijp'), as he described himself.

The improvements that Leeghwater introduced into the construction of the drainage-mill were not fundamental and he obtained no patents for them. In fact he was granted two patents only, one of them in 1605, in company with

Pieter Pieters and William Pieters, for a device for 'going under water', which attracted the attention of Prince Maurice, and was claimed to have practical value in making possible underwater repairs to bridges, sluices, and the like. But in 1608 the 'laying dry' of the Beemster, the largest of the inland lakes of the north Netherlands (figure 202), was begun, and Leeghwater was appointed 'to undertake the manufacture and erection of the water-mills' (figure 205). Four years later, in May 1612 (forty years after the first plans for the draining of the Beemster had been formulated), the work was completed and Leeghwater's reputation was firmly established.

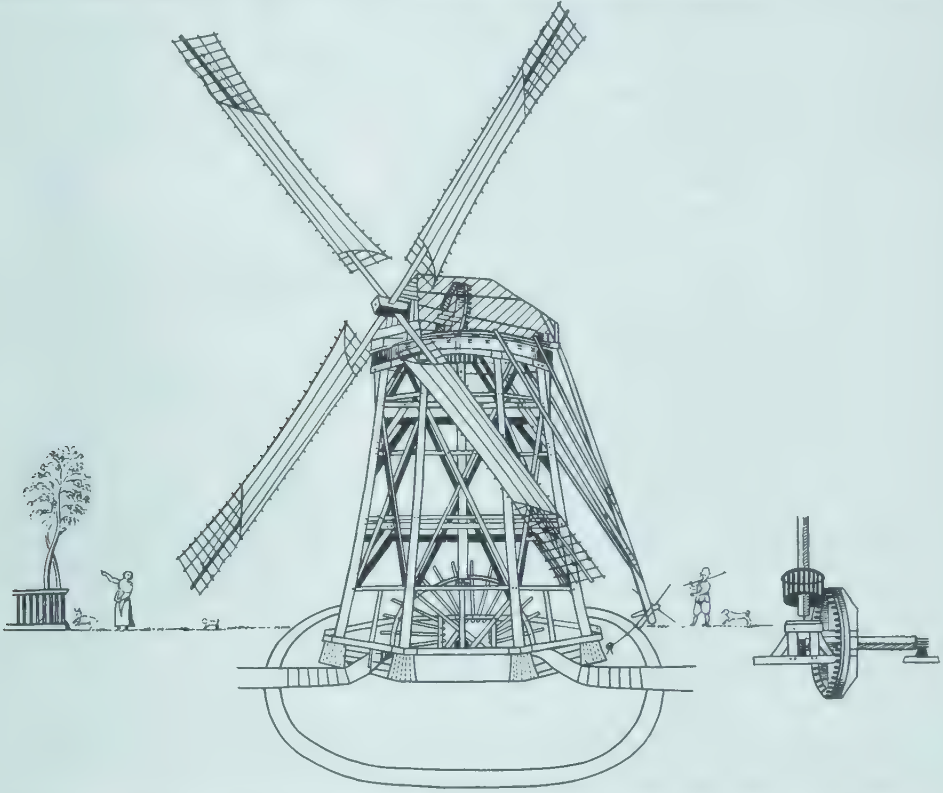

FIGURE 205—*Drawing by Leeghwater of a mill used in draining the Beemster polder. The scoop-wheel rotates clockwise and the outflow is to the left.*

It was in the Beemster that Leeghwater developed the system of multi-stage water-lifting in which the water was lifted successively by two, three, or four scoop-wheels working in series from the lowest level of the polder up to the level of the *ringvaart* (vol II, figure 627). The system was not his invention, for it was known in the sixteenth century, but it found its full application under Leeghwater in the Beemster, and in many polders on which he was successfully employed.

Leeghwater represents the best type of mill-maker and drainage engineer in the Golden Age of the Netherlands in the first half of the seventeenth century. His fame spread beyond the confines of his own country, and he travelled widely in the Netherlands and abroad (p 319). His best-known monument is a work which he never carried out, the draining of the Haarlemmermeer, vividly described in his *Haarlemmermeerboek* ('Book on the Meer at Haarlem') published in 1641[1] [4]. A striking feature of his plan (figure 206) was his proposed employment of no fewer than 160 drainage-mills; had financial backing been forthcoming (Leeghwater's estimate of the cost was 3 600 000 guilders) the scheme could well have succeeded, as it did in 1852 with the aid of steam pumping-engines. The breadth of the concept gives some measure of the man.

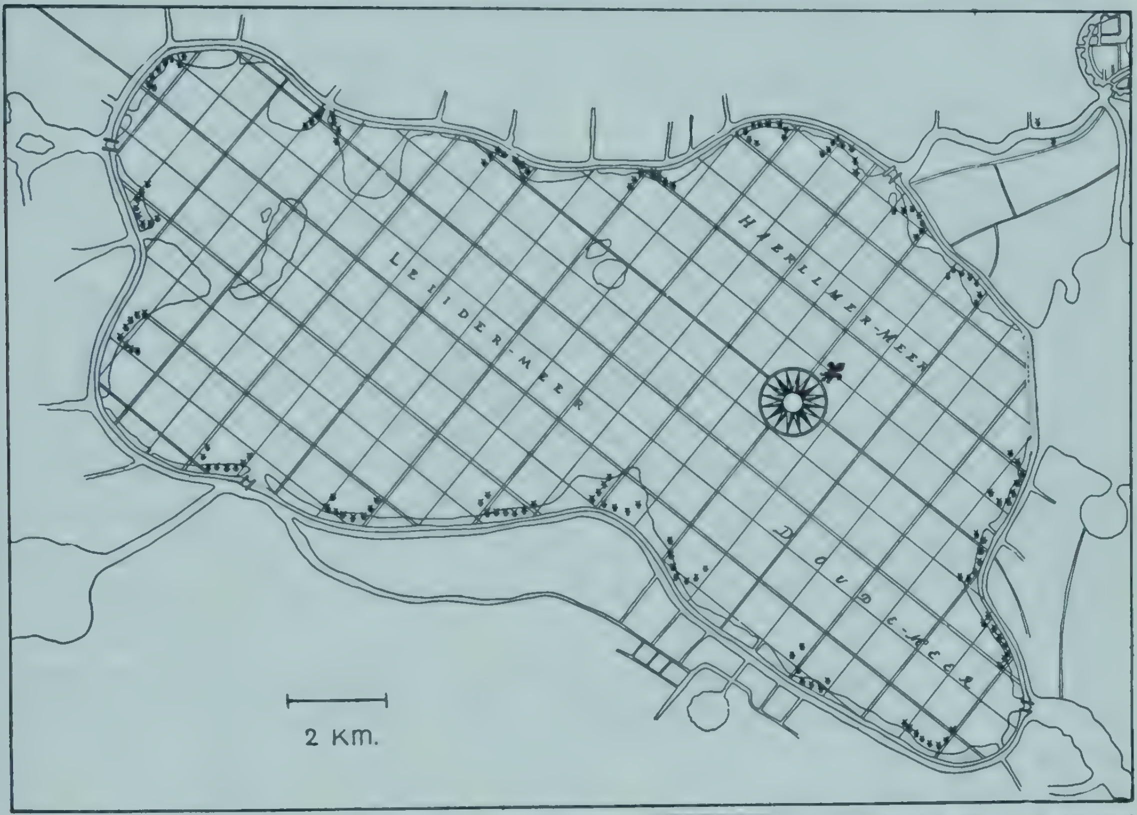

FIGURE 206—*Leeghwater's original plan for draining the Haarlemmermeer, 1629. The area was to be drained by a regular series of channels arranged at right-angles, from which water was to be raised by the windmills closely spaced round the edge of the meer.*

Clearly neither Stevin nor Leeghwater was the inventor of the drainage-mill, and it would be impossible to assign that role to any one individual. One whose part in its development must be mentioned is Cornelis Corneliszoon of Uitgeest,

[1] A thirteenth edition of his scheme was printed in 1838.

who was first granted a patent in 1597 for a design embodying a windmill-driven two-throw crank operating twin reciprocating pumps, a novel but not entirely satisfactory design. His fame mainly rests on the construction of the wind-driven saw-mill, but he has the added distinction of having been granted a patent by the States-General in 1602 for a pump which appears from his obscure description to have been an early design of centrifugal pump, or at least a device for using centrifugal force to raise water. The development of this invention had to wait some 250 years, when the first centrifugal pump for fen-drainage was installed in England.

Too much emphasis, however, must not be laid on the importance of the drainage-mill in land-reclamation at this time. Without it, it is true, the extensive *droogmakerijen* of inland meers might never have been undertaken, but it must be realized that, between 1540 and 1690, 80 per cent of the land reclaimed in the six principal provinces of the Netherlands (some 167 260 hectares) was land embanked from the sea. Thus this extension of the land was mainly achieved by the technology of dike-construction and 'assisted accretion'. In such work the early existence in the Netherlands of administrative organizations for the centralized control of general drainage systems, the *Hoogheemradschappen* (Main Polder Boards), whose foundation goes back as far as the year 1200, and the smaller bodies within their framework, was an important factor. Though these organizations were not creations of the sixteenth and seventeenth centuries, without their existence it is doubtful whether the technological advances made during this period would have occurred. Certainly they would never have been utilized to the full.

II. ITALY

The problem in Italy of *la bonifica*, or land-reclamation in its widest sense, must be considered from a geographical point of view if the special nature of the problem, and its dissimilarity from that of other European countries such as the Netherlands, England, and France, is to be understood. A long, comparatively narrow strip of country separated from the rest of Europe on the north by the great semicircular barrier of the Alps, Italy is divided roughly from north to south by a mountainous spine, down which on either side descend a multiplicity of rivers, often snow-fed mountainous torrents in their upper reaches. Its coastline is extensive. All these factors combine to create a problem to be solved fundamentally by the training and regulation of the rivers. Regulation of rivers forms the key to *la bonifica*, and to the technology on which it is based. For *la bonifica* always has been, in Italy as in other countries, essentially a hydraulic problem with the double purpose of improving both health and agriculture, an age-long problem of the removal of stagnant waters resulting from the flooding of rivers.

The history of *la bonifica* has three important characteristics. First, it has its roots in the works of the Roman emperors roughly 2000 years ago, even if its development has not been continuous. Secondly, and consequently, it has no clear-cut beginning in the sixteenth and seventeenth centuries as in the case of England and France. Thirdly, land-reclamation in Italy was carried out independently of the skill and experience of the Netherlands, developing in this period an indigenous technology with a scientific basis.

The drainage and irrigation works of the Roman Empire fell into decay with its dissolution, and many centuries passed before the religious houses, particularly the Benedictine and Cistercian foundations, attempted to revive such works. Their attempts, though small and unco-ordinated, provided the pattern for the developments of the sixteenth and seventeenth centuries. Thus in the seventh century the Benedictine abbeys of Palazzolo, Monteverdi, and Salvatori had executed works of drainage in many of the marshes of the plain of Lombardy. In the twelfth century the Cistercian abbey of Chiaravalle had carried out the irrigation of the Vettabia di Milano, and about the same time similar monastic work was done in the Bassa Valle Padana. By the early years of the sixteenth century numerous undertakings of a minor nature were in being, but the initiative was passing from the religious houses to the landed proprietors in the semi-independent states, to the councils of such wealthy and powerful cities as Venice and Milan, and particularly to the Papal State and the successive popes.

At the same time there was a growing recognition of the need for special organizations to study, finance, and control *la bonifica*. Early in the sixteenth century the State of Venice had appointed its *ufficiales supra canales* and *ufficiales paludum* (marsh officers), the city of Verona had constituted its *Collegio per il fiume Adige* for the control of that river, and Florence in 1549 had created *ufficiales di fiumi*, *ponti e strade* (officers for rivers, bridges, and streets), among whose functions were the regulation of the rivers and the prevention of flooding. The importance of these and similar organizations lies in the incentive that they provided for a scientific technological approach to practical hydraulic problems. Thus, for example, under the control of the *ufficiales di fiumi* of Florence there worked one of the outstanding hydraulic engineers of the sixteenth century in Italy, Bernardo Timante Buontalenti (d 1608), appointed city engineer by the Medici, who carried out much original work of improvement on the Arno.

A significant feature of these official bodies was that they had sufficient authority to ensure replacement of individual and local works of river improvement, and so on, by systematic control of the main river and its tributaries as a single unit. In 1558 Girolamo di Pace, one of the *ufficiales di fiumi*, wrote a general review of the whole Arno situation, and in the forty-five years between 1558 and 1603 masses of reports and schemes for the improvement of the Arno were submitted to that body, all of which had to be sifted and evaluated.

Perhaps the most important hydraulic engineer in Italy at this period was the Florentine Antonio Lupicini (*c* 1530–98), a man whose reputation spread far beyond the bounds of Italy. While his experience was broad, he confined his activities to hydraulics and fortifications, principally the former, and thus became what was indeed rare in those days, a specialist. Lupicini's fame is perpetuated in six books, of which the two most interesting from the hydraulic point of view are: *Discorso sopra i ripari del Po e d'altri fiumi che hanno gl'argini di terra posticcia* ('Discourse on the defences of the Po and other rivers with artificial embankments of earth'), 1587, and *Discorso sopra i ripari delle inondazioni di Fiorenza* ('Discourse on flood-protection at Florence'), 1591 [5]. The former deals with remedial works on the river Po, partly for navigational purposes, partly for flood-prevention. The latter deals exclusively with flooding and its prevention. Lupicini was fully acquainted with methods of dike-construction and the design and building of retaining-walls, groynes, and diversionary banks, the science of which was then as fully developed in Italy as it was in the Netherlands. But it is clear that the mud-dikes, the *slikkerdijk*, the *wierdijk*, and similar constructions employed in the Netherlands for polder-reclamation could not be used for the fast-running and often turbulent rivers of Italy. Thus the Italian engineers had to build pile-dikes, masonry walls, stone pitching, and various forms of mattress protection and fascine-work, with which in consequence they became fully acquainted. It might be said, indeed, that Lupicini had developed original ideas on mattress protection, because in his *Discorso sopra i ripari del Po* of 1587 he discussed in detail the causes of bank-erosion and describes the remedy that he had designed to prevent it.

His method was to employ a 'circular structure' consisting of logs set about 4 ft apart, cross-connected and bound with willow-sprigs, the whole forming a mattress one end of which was attached to the shore and the rest unrolled to fall into place over the point of erosion. The whole was then weighted with stones to keep it in place. As to bank-construction, Lupicini laid it down that in general the height should be 4 ft above the highest ascertained flood-level, with the base three times the height. This, however, might be thought to give too steep a slope, but he specified that the banks should be constructed of alternate layers of earth and straw, the former 10 ft thick, levelled and rammed, and by this means he was able to employ satisfactorily the steep angle of repose. It must be emphasized that Lupicini's constructional principles were devised for river-regulation, not for coastal protection.

The whole story of *la bonifica* in the sixteenth and seventeenth centuries is a complicated and fragmentary one, but perhaps the attempts to drain the Pontine Marshes provide a symptomatic insight into that story, although the problem was a somewhat specialized one (figure 207). The Pontine Marshes, then in the territory of the Papal State, cover an area of some 300 square miles south-west of Rome, and comprise a coastal strip lying between the Tyrrhenian Sea and the Lepini mountains, from which flowed many minor and often turbulent rivers. The efforts of successive emperors to drain the marshes had been partially successful, enabling the Appian Way to traverse the area. Their works had decayed, and by the opening of the sixteenth century, in spite of the well intentioned efforts of earlier popes, the region was nothing but a malaria-infested marsh. In 1514 Giovanni de' Medici, Pope Leo X, granted to his cousin, Julius de' Medici, later Pope Clement VII, a concession for the work of drainage, which resulted in the cutting of a canal named *Fiume Giuliano* after the pope's brother, Giuliano de' Medici, in whose service Leonardo da Vinci then was. Probably at this date Leonardo prepared a map showing his scheme for the drainage, in which he proposed to re-cut the ancient Roman canal running parallel to the Appian Way, and to use it (following the Romans) as a cut-off channel for the waters coming down from the Lepini mountains (plate 19). An additional channel was to be constructed at right-angles to the cut-off channel to assist the discharge to the sea of the waters of the rivers Livoli and Ufenti. There was also a second subsidiary scheme for improving the *Rio Martino*, a Roman canal traversing the low ground between the Appian Way and the sea, but, in the end, little or nothing appears to have been done and the whole proposal was dropped on the death of Leo X in 1522.

After this abortive attempt some sixty years had elapsed when early in 1586 Ascania Fenizi, an engineer from Urbino, placed before Sixtus V (1585–90) a plan for draining the marshes with the financial aid of wealthy merchants of Urbino. This pope must be given credit for supporting a scheme that very nearly succeeded. He granted a concession to Fenizi for the laying-dry of all the territory of Terracina, Piperno, and Sezze, $5\frac{1}{2}$ per cent of the drained land to be allotted to the *Camera Apostolica* or papal treasury. Sixtus had already been active in promoting other hydraulic works; thus he had been instrumental in improving the ports of Rimini, Ancona, and Civita Vecchia, and in draining the marshes of Ravenna and the lands at the mouth of the Tiber. Work on the new undertaking began at once, 2000 men being employed, and was completed in January 1589. Sluices were built for the control of the several rivers and streams coming down from the high ground, new minor canals were cut, and a main canal, the *Fiume Sisto*, was dug. After the death of Sixtus in 1590 the works fell into decay, the marshes returned to their pristine state, and malaria again ravaged their inhabitants.

Next on the scene was a Netherlander, Nicolaas Corneliszoon de Witt, of Alkmaar, who presented himself in Rome in 1623 with a scheme for draining the Pontine Marshes. He was granted a concession for the purpose in 1637 by Pope Urban VIII. The undertaking was to be financed by a company of Catholic merchants from both Italy and the Netherlands, but when de Witt died in the following year the scheme collapsed, as did a later one in which another Netherlander was interested.

It was not until near the end of the seventeenth century that the attempt to drain the Pontine Marshes was renewed, again by a Netherlander, Cornelis Janszoon Meijer, perhaps the most important of the engineers from the Low Countries who carried out hydraulic works in Italy. A native of Amsterdam, by 1674 Meijer had made a name for himself in Rome as an engineer of considerable skill. In 1676 he submitted to Innocent XI plans for draining the marshes, on which the pope instructed an Italian engineer to prepare a report. As a result of this report Meijer studied the problem again and in 1678 wrote a memoir ('On the way to drain the Pontine Marshes'); this was published in 1683 and was illustrated by a map made by Giovanni Battista Falda (figure 207) [6]. He did not live to carry out his plans; they were, however, executed by his son, with a lack of success largely due to the active opposition of the inhabitants of the area.

Meijer's more important book, *L'Arte di rendere i fiumi navigabili in varij modi con altre nuove inventioni, e varij altri segreti* ('The Art of making rivers navigable in various ways, with other new inventions and various other secrets') (1696), written when he had become a member of the *Accadèmia Fisicomatematica* of Rome, shows him to have been a man of wide accomplishments. It deals with a variety of subjects and mechanical devices of all kinds, such as boat-lifts, caissons, cranes, mechanically propelled carriages, and so on. While it is likely that in many instances he was acting merely as a reporter, the book does give some idea of the state of certain branches of technology, particularly hydraulic technology, in Italy at that period. He writes of methods of remedying the inundations of rivers, including methods for preventing the inundation of the provinces of Bologna, Ferrara, and Ravenna. He describes the work of pile and fascine construction with which he had repaired the damaged port of Pesaro, discusses the use of dredgers, and discourses on river-training and bank construction that he had carried out on the Tiber in 1696 for Pope Innocent XII (figure 208).

By the end of the seventeenth century the practice of *la bonifica* was highly developed, but we must now mention a most potent factor in land-reclamation and drainage in Italy, particularly towards the latter end of our period, namely the researches of scientists into the behaviour and regulation of rivers, a factor which to a great extent differentiated the conditions there from those in other European countries. If it is true that the work of Galileo Galilei (1564–1642) and, to a lesser degree, of Simon Stevin (1548–1620) in hydraulics represents the first advance in that science since Archimedes, it is equally true that the scientific researches of Benedetto Castelli and his successors into the flow of rivers

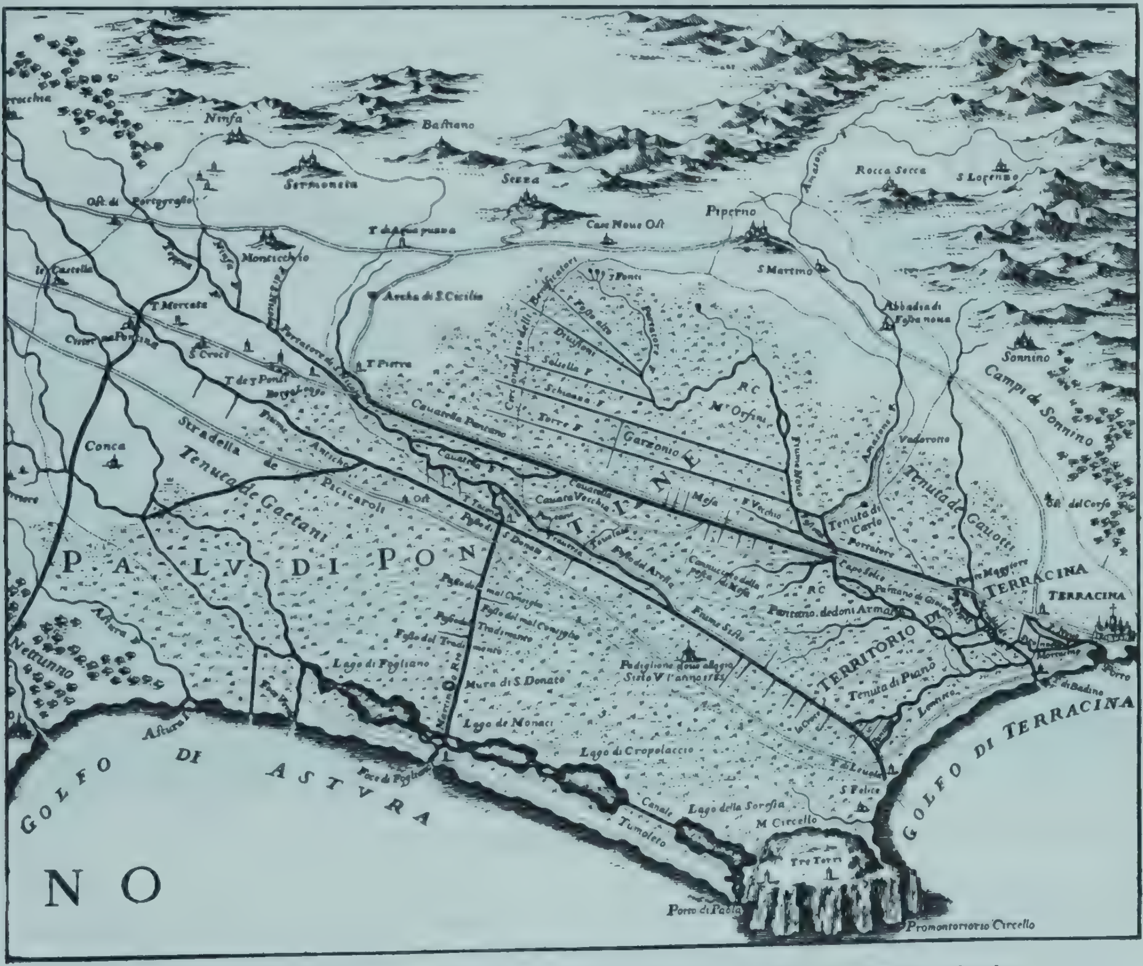

FIGURE 207—*G. B. Falda's map (1678) of Meijer's scheme for draining the Pontine Marshes.*

represent the beginning of a new phase in the art of land-reclamation in Italy. Galileo himself was no mere theoretical worker in this field. Apart from the fact that the State of Venice had in 1594 granted him a patent for the erection of a water-raising machine, he had at one time been superintendent of the waters of Tuscany. There is still extant his report on the river Bisenzio written in January 1630, after an inspection made with the two engineers Bartolotti and Fantoni.

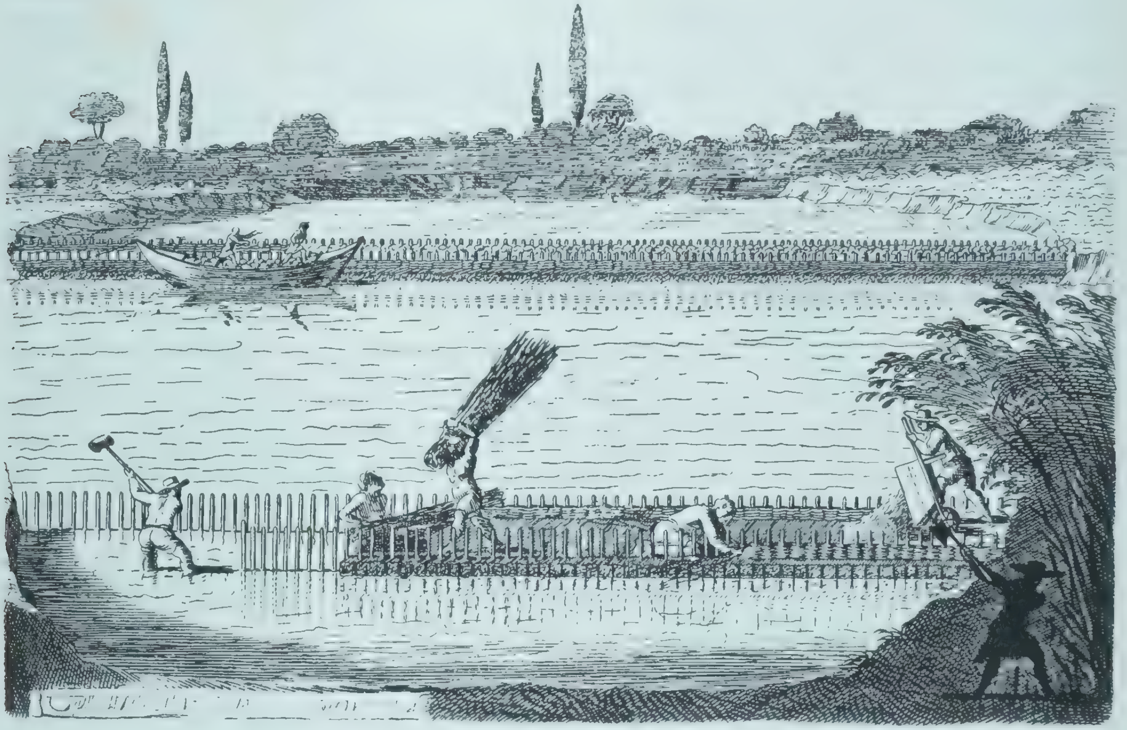

FIGURE 208—*The construction of* krebbingen *as a means of defining the banks of a river. From Meijer, 1683.*

Benedetto Castelli (1577–1643), a student under Galileo at Padua, had been employed in 1623 by Ferdinand, Grand Duke of Tuscany, to remedy flooding in the valley of Pisa between the river Serchio and the Fiume Morto. Then he attracted the notice of Urban VIII and in 1625 was appointed by him to assist Ottavio Corsini, superintendent of the general drainage of Tuscany for the areas around Bologna, Ferrara, and Commachio lying between the rivers Po and Reno. It was during this period that he wrote his book *Della misura dell' acque correnti* ('On the measurement of running waters'), published in 1628 (not posthumously as is often incorrectly stated) [7]. This was not just an abstract philosophical expression of theoretical ideas, but was based essentially on a combination of theory and practical observation applied to the creation of remedies for actual inundations and other hydraulic problems, and thus initiated a sound hydraulic technology. This technology expanded as scientific inquiry was extended.

Vincenzo Viviani, who played a large part in founding one of the first great scientific societies, the *Accadèmia del Cimento*, in 1657, was another of Galileo's most distinguished pupils who did important work as a practical hydraulic engineer. Viviani succeeded Galileo as superintendent of the waters of Tuscany, and successfully executed on the river Bisenzio training-works which Galileo himself, in his earlier report representing a less developed knowledge, had condemned as useless.

Castelli's book was followed by two important publications, the *Della natura de fiumi* ('The nature of rivers') of Domenico Guglielmini (1697) [8], and the complete *Architettura d'acque* ('Hydraulic architecture') of Giovanni Battista Barattieri (1699)[1] [9]. Barattieri was engineer to the Duke of Parma, and his book, based on his own observations and experiments and also on the earlier work of Castelli and Corsini, to both of whom he paid due acknowledgement, is perhaps the best example in our period of a practical and scientific work on the problems of river regulation.

The distinguished Italian mathematician of the eighteenth century, Paolo Frisi (1728–84), wrote with pardonable pride that 'Hydraulic architecture arose, advanced, and almost reached perfection in Italy, where they have written on every point connected with the theory of torrents and rivers, the conducting and distributing of clear and turbid waters, the slopes, the directions, and the variations of channels; and, in one word, on the whole range of Hydrometry and Hydraulics'. What certainly can be stressed is that *la bonifica* was in the sixteenth and seventeenth centuries, as indeed it is today, based fundamentally on river-training and regulation, the science of which was developed so effectively in Italy in the seventeenth century.

III. ENGLAND AND FRANCE

The geographical and economic situation of the 'drowned lands' of England in the sixteenth century was entirely different from that in either the Netherlands or Italy. Some 700 000 acres of fenland, part marsh, part subject to periodic flooding, lay in the eastern counties of Lincolnshire, Cambridgeshire, Huntingdonshire, and Norfolk, forming what might be termed a land bay extending inland on its longest axis some 35 miles from the shores of the Wash (figure 209). There was no imperative need to reclaim the land for purely agricultural reasons, and incursions of the sea, on a comparatively limited coast-line, were a danger of restricted extent and infrequent occurrence, largely counteracted by the embankments constructed on the low-lying Lincolnshire coast in pre-Roman days. The four rivers flowing through the Fenland—the Ouse, the Nene, the Welland, and the Witham—were comparatively small and had none of the characteristics of the mountainous torrents of Italy. The development of a systematized reclamation of the Fens in the sixteenth and seventeenth centuries was confined mainly to what was termed the Great Level—later the Bedford Level—between the river Nene and the uplands of Norfolk, an area of some 302 000 acres, to the exclusion of the Lincolnshire fens. In the Great Level the ancient Fenland abbeys had carried out limited works of reclamation and drainage, but with the final Dissolution in 1540 their influence was removed, leaving behind a vacuum to be filled by the financial speculator and adventurer, whose object was capital gain. Indeed it is to the often despised profit-motive that we owe the initiation and completion of the so-called 'draining of the Fens' in the seventeenth century.

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[1] The two parts of this treatise had been published separately in 1656 and 1663.

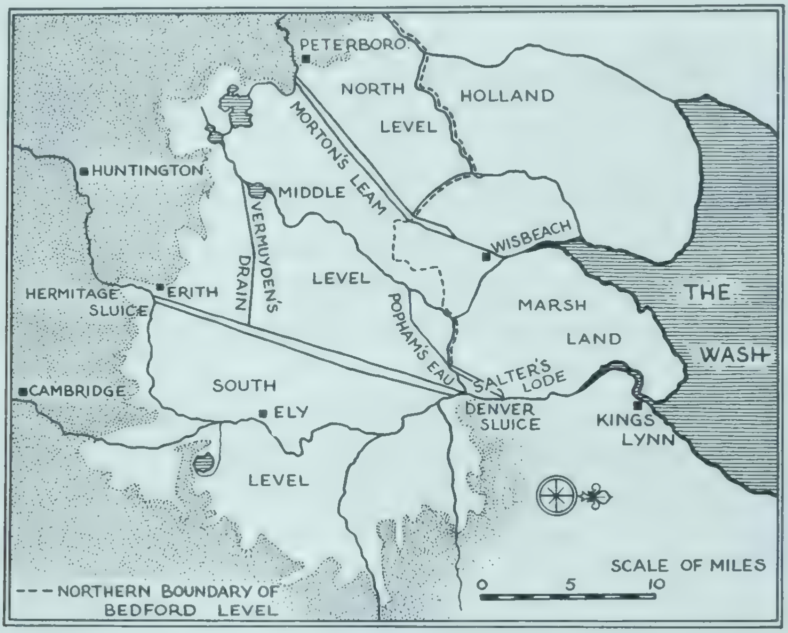

FIGURE 209—*The Great or Bedford Level on the completion of Vermuyden's scheme in 1653. After Badeslade's map of 1724.*

The first positive step towards a draining of the Great Level came from Humphrey Bradley, the Brabanter from Bergen op Zoom who probably owed his name to an English father, an important functionary in the House of the Merchant Adventurers there. He was probably introduced into England by

Joachim Ortell, an emissary from the States-General, and in 1584 submitted to Sir Francis Walsingham an 'Advys' on a scheme for the reconstruction of Dover harbour. In a letter of March 1588 from the Privy Council to the commissioners of sewers of the chief Fen counties, Bradley, John Hexham, and Ralfe Agas were recommended as persons 'able to make viewe and platt [map] for the several fenns, the true dyssentes of waters, and qualities of soile through which waters should be carried', that is, they were skilled surveyors and able to take levels. As a result Bradley submitted a 'Treatise' on the draining of the Fens to Lord Burghley in December 1589.

This 'Treatise' is noteworthy in two main particulars, for it was the first comprehensive proposal for draining the Great Level, as opposed to the piecemeal attempts made hitherto, and it was also a scheme prepared by a man skilled in the arts of drainage and diking (as will appear later), and based, therefore, on sound technological principles and practice. It was, too, founded on a reasonably accurate survey, considering the limitations of instruments and methods of survey at that time (ch 20). That is an important point, because the most essential requirement in a wide region like the Fens was an accurate survey of the whole area. John Hexham and Ralfe Agas, named in the Privy Council letter, were both reputable surveyors. By this date the science and practice of surveying, through its developments during the previous eighty or ninety years, had reached the stage where all the basic items of the modern surveyor's equipment were in use.

Bradley's 'Treatise' gives no figures for the levels on which his scheme was based, but some years later, in 1597, Agas when writing to Lord Burghley stated that in his survey he had levelled throughout the Fens down to the outfalls of the rivers. Bradley himself had said that in the Fens 'practically the entire surface of the land is above high sea-level', and had gone on to point out that 'the only way to redeem the land from the waters is to draw off the waters by directing them along the shortest tracks . . . in canals dug of such width and depth as can serve to make the waters run to the sea'. He emphasized that his purpose could be accomplished by a gravitational scheme without recourse, as he said, 'to embankments, machinery, mills, and inestimable expense'.

Thus the relative land- and sea-levels were such as to render drainage-mills unnecessary in general, but there is little doubt that even in the year 1588, and possibly earlier, such mills were in use in certain individual fens. Whether they were windmills or horse-mills it is impossible to tell. What is known is that even in 1580 Peter Morrice (or Morris), presumably a Netherlander, had been granted a patent for draining 'certaine fens . . . by certaine engines', while applications for similar patents had been made by other Netherlanders about 1578. These, however, were merely individual efforts, and when Humphrey Bradley retired disappointed to Bergen op Zoom, after a further futile petition to Lord Burghley in 1593, a co-ordinated scheme for the reclaiming of the Great Level—the only method by which a true reclamation could be accomplished—receded into a future nearly forty years away. The problem was less technical than financial and human. But Bradley is important in the history of land-reclamation in England for having enunciated a clear-cut scheme in which the Fens, or at least the Great Level, were considered as a single unit. Whatever may have been the solid achievements of Cornelis Vermuyden (p 320), he undoubtedly owed a lot to his predecessor, a fellow Netherlander.

The problem of draining and reclaiming low-lying grounds in France was different again. Fundamentally, as in England, it involved the prevention of the flooding of flat areas by slow-moving rivers, but in France there was no single large 'drowned and surrounded' area such as the Fens. In contrast to the Netherlands, the reclamation consisted principally of draining marshes rather than reclaiming land from the sea. The real establishment of a systematized land-reclamation owes everything to Henri IV (reigned 1589–1610). It is true that some attempts at minor reclamation had been made centuries earlier by the religious houses of the Benedictines, and isolated schemes had been attempted in the years immediately preceding Henri's accession. Thus in 1587 an attempt had been made by the Mareschal de Matignon to drain and cultivate the marshes around Bordeaux, where periodic epidemics of ague or malaria carried off the inhabitants sometimes in thousands. But the initial impetus to Henri's wide conception came indirectly from the claims of war, which constantly pressed upon him for some time after his accession. On 18 June 1596 the States-General of the Netherlands reported that they had received from the French king through his ambassador a request that they should send to France 'four qualified individuals experienced in the art of diking'. In the following month Humphrey Bradley was instructed to travel to France with Jan Gerritszoon from Holland and another, unnamed, diker from Zeeland, there to engage in 'works of diking' on behalf of the king. But the important point lies in the exhortation that they should assist the king 'in all warlike operations'.

This was the reason for Humphrey Bradley's journey to France. What military engineering Bradley and his friends did we do not know, but when major hostilities had ceased Bradley remained in the king's service by royal request. Henri then determined to undertake large-scale land-reclamation as one of the many means of rehabilitating the country, and in 1599 Bradley was appointed *maître des digues du royaume* with a practical monopoly to drain low-lying grounds in the whole of France. He had already, on orders from the king in 1597, begun the drainage of low grounds at Chaumont-en-Vexin (Oise).

No particularly novel technological development grew out of Bradley's work in France, and it will suffice here to say that, in due course, he, or rather *L'Association pour le dessèchement des marais et lacs de France* founded by him and largely financed by fellow-Netherlanders, successively drained the marshes of, among others, Saintonge, Poitou, Normandy, Picardy, Languedoc, Provence, and the lake of Sarlièves (Puy-de-Dôme). This *Association* was, perhaps, the most noteworthy and indeed the all-important factor in this work in France. It arose out of the first edict of 1599, was officially constituted by a second edict of 1607, was renewed by a further edict in 1639 until 1655, and continued until the repeal of the Edict of Nantes in 1685. Its importance lies in the fact that it represented a coherent organization, administrative, financial, and technical, of supreme necessity in large-scale and widely distributed undertakings of this nature. It took its pattern from the similar organization, the *Hoogheemradschappen*, of the Netherlands (p 308).

It has been noted earlier (p 307) that Leeghwater visited France in 1628, when he was invited by the Duc d'Épernon to survey and drain the marshes of Lesparre (Gironde). We may guess that Bradley was still alive.[1] The *Association* was certainly still in existence and it is difficult to see why, or how, Leeghwater should be called in to undertake this work and thus encroach on the preserves of the *Association*. The Duc d'Épernon may, of course, have considered a second, independent opinion necessary. Bradley's conceptions were not always right. He certainly had made mistakes earlier in his calculations for the Burgundy canal, but knowledge of hydrodynamics and of the flow and slopes of rivers and canals was at that time still elementary and awaited the developments in Italy of about the middle of the century.

The course of draining the English Fens had Bradley been granted permission to proceed with his plans in 1589 must be a matter of conjecture. Between that date and 1630, when the first undertaking in the Fens came into being, fruitless discussions went on interminably against a background of financial speculation divorced from technical considerations. English financial interests waged a struggle with Netherlands financiers to obtain concessions, the crown balancing the scales somewhat unevenly in its own interest. In 1630, however, Francis, fourth Earl of Bedford, was appointed 'undertaker' for the drainage of the Great Level, being joined by thirteen other Englishmen prepared to 'adventure' their capital on the project. Cornelis Vermuyden (? 1590–1677), a Zeelander from the Isle of Tholen, was appointed director of works or chief engineer. He had first come to England in 1621 and a few years later had been given by Charles I the concession to drain the 70 000 acres of Hatfield Chase in Yorkshire, a scheme financed almost entirely by capital from the Netherlands. The reclamation of the Great Level by Vermuyden, virtually completed in 1653, represents the one great land-reclamation scheme in England of the seventeenth century, and indeed of all time, and some idea of its importance may be gained from the fact that the total area involved, about 307 000 acres, is equal to seven-tenths of the total area reclaimed in the Netherlands in the 150 years between 1540 and 1690.

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[1] The date of his death is unknown, but it must have been after 1625, and before 1639.

The original plan and map of Vermuyden of 1630 have not survived (they probably perished in the Fire of London, 1666) but the principles on which he based his later, and extended, scheme are still extant in his 'Discourse touching the Drayning [of] the Great Fennes' written in 1638 and published in 1642 [10]. From this it is clear that the plan was founded on a purely gravitational system, Vermuyden deciding, as had Humphrey Bradley, that there was sufficient fall to the river outfalls in the Wash because, in Bradley's words, 'practically the entire surface . . . is above high sea-level'. Very little is known of Vermuyden's activities before his arrival in England in 1621, but recently there has come to light a map of the area around Steenbergen in Brabant made by him and signed 20 October 1615: 'Map and project of the drowned lands lying in Brabant across from the town of Tholen . . .' (*Caerte ende ontwerp van de verdroncken landen gelegen in Brabant tegens over de stadt Tholen . . .*). This shows that he was a skilled surveyor and even in 1615 could prepare plans for the draining of 'drowned' lands.

When he embarked upon the Great Level undertaking he had behind him not only his experience in the Netherlands but that gained in Hatfield Chase, and it must be admitted that there he had made some mistakes. For such drainage projects as Hatfield Chase and the Great Level, with their treatment of involved river-systems, were somewhat different from, and more complex in diagnosis than, the embanking of a polder or the draining of an inland meer in the Netherlands. There such works were based on an established technology of dike-construction, canal-excavation, the building of sluices, and so on. Vermuyden had the advantage of a knowledge of that technology, almost entirely lacking in England, but his task involved a combination of the Netherlands problems with the Italian problem of river-regulation in a simplified form. He had also to contend with the peculiar river-outfall conditions in the Wash. There was no ready-made solution to this combination; any faults in Vermuyden's general scheme were faults of initial diagnosis, not of execution. His system worked satisfactorily for a time after its completion in 1653, and would have continued to work had not the lowering of the land-surfaces through the shrinkage of the peat-lands especially, and of the silt-lands to a lesser degree, destroyed the one simple hydraulic factor on which that system was based, namely gravitational discharge. When this discharge ceased to function a new technology, involving the mechanical raising of water, was bound to be needed just as it had been necessary earlier in the Netherlands for similar reasons.

The extent to which the land shrank through desiccation was itself a measure of the effectiveness of Vermuyden's scheme of drainage. As its effectiveness deteriorated, the need for water-lifting became apparent, even if the true reason for that need was not well understood. When in 1664 William Dodson wrote his 'Designe for the perfect draining of the Great Level . . .' [11] he recognized the fact of land-shrinkage without appreciating the reason for it, yet made no suggestion that pumping had become generally essential in the Great Level. Dodson had worked under Vermuyden when the latter had been director of works and had succeeded him on his retirement in 1655. He had travelled extensively in the Netherlands and had seen how 'the Bempster, the Skermer, and the Wart, &c, . . . are all drained by a multitude of mills, each mill costs near six hundred pounds sterling' (plate 20). Indeed, he had been granted five patents in the Netherlands, relating to drainage-mills, between 1657 and 1660.

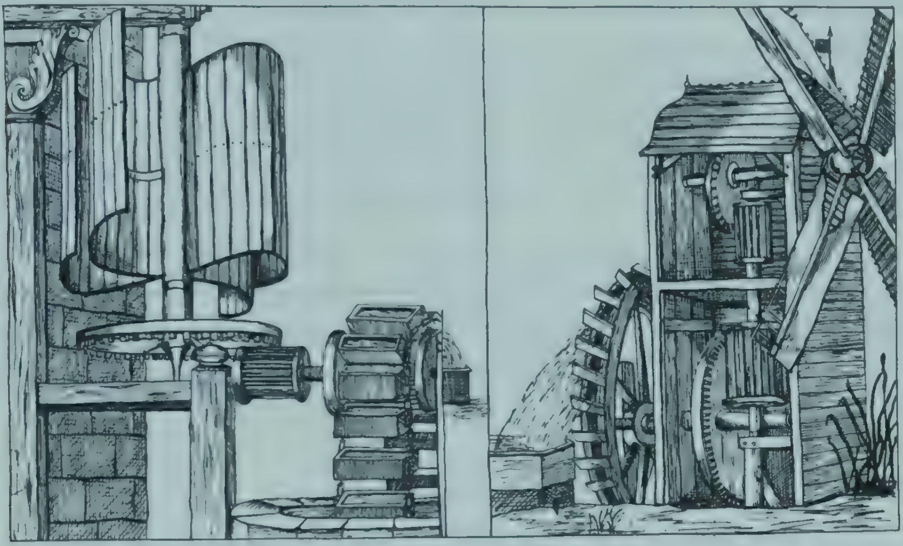

FIGURE 210—(Left) *Vertical windmill driving chain-of-buckets in a well;* (right) *fixed horizontal windmill driving scoop-wheel. 1652.*

About the time of the completion of Vermuyden's scheme in the Great Level Walter Blith published 'The English Improver Improved or The Survey of

Husbandry Surveyed' (1652), and from his comments on the Fen drainage it is quite clear that drainage-mills were fairly common in individual fens although not part of the main scheme of reclamation and drainage [12]. They were, as Blith tells us, either 'wrought by the wind, or by the strength of horse; yea possibly by the strength of two or three men', and could raise the water either by a scoop-wheel 'or else by a good chain pump, or bucket work both of which may be made into a windmill-engine' (figure 210). These various forms of small drainage-mills were of comparatively primitive construction, and when eventually general pumping became imperative the technology of drainage-mill construction was largely borrowed from the Netherlands. Inevitably this technology became naturalized in time, and by the end of the seventeenth century the draining of the Fens as opposed to the initial reclamation had ceased to be the prerogative of Netherlanders. The chief obstacle to its success was the almost entire lack of a central administrative system such as existed in France and the Netherlands. The Fen drainage was at the mercy of commissions of sewers, whose limited powers were less fitted to deal with the wider problems of the seventeenth century than to contend with the simple parochial details facing them in earlier times. Indeed, a major fault was a failure to appreciate that the draining of the Fens was both a technological and an administrative problem.

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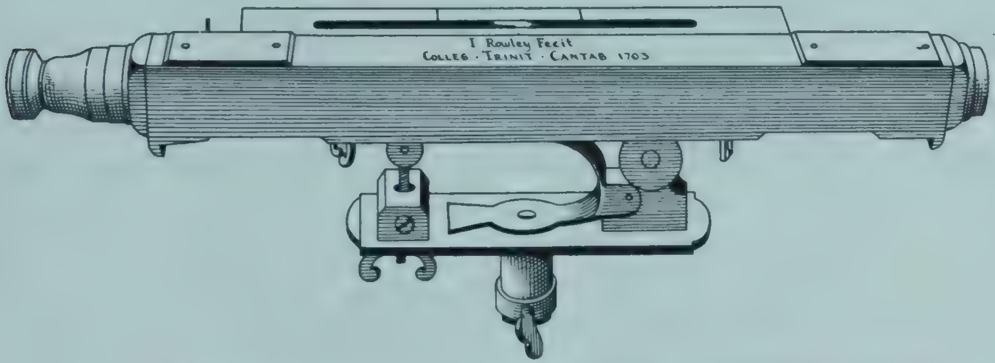

An early surveying level with telescopic sights and bubble, made by John Rowley, 1703.

13

MACHINES AND MECHANISMS

A. P. USHER

I. MACHINES IN GENERAL

THE techniques of machine-building are important in any period, and should not be thought of as involving only problems of mechanics without significance for the prime process of innovation and invention. In the sixteenth and seventeenth centuries, the character of technological change is as clearly revealed by techniques of machine-construction as by specific innovations. New skills in drawing and engraving made it possible to present many novel ideas in the form of sketches and plans, even if they were not at the time capable of being realized. Such presentations provide a positive record of the conceptual stage of invention that is not so fully available for earlier periods, though it is seldom entirely lacking. Outstanding characteristics of this time were the improvement of many well known devices and machines, and the development of the capacity to build more sophisticated and more closely articulated mechanisms. Probably, for example, the great increase in the use of the suction-pump was due to improvements in its construction: this led in turn to the complete analysis of the vacuum and to the understanding of a whole series of power-devices using air- and water-pressure. Thus an engineering achievement led to basic developments in pure and applied science, and laid the foundations for modern power-engineering. Because the full accomplishment came in the eighteenth century, its beginnings are often forgotten.

It is not easy to trace the development of the technique of machine-building accurately. Contemporary accounts do not always give details of construction, and it is unwise to draw inferences from sketches and plans. Fortunately, there is much detail in Agricola's *De re metallica* (1556), at the beginning of the period; while the *Architecture hydraulique* (1737–53) of Bernard Forest de Belidor (1693–1761) provides descriptions over a half-century or more at the end. With these and other works a chronology of machine-construction can be established.

An orderly process can be discerned in the complex array of details, if we can apply to these historical problems the principles of analysis developed by Reuleaux.[1] It is necessary to study the essential mechanical elements and the efficiency with which they are employed, singly or in combination, as well as comprehensive trains of mechanism. New proficiencies in engineering are revealed by increased accuracy and definition in the interaction of the parts of machines. In general, the sixteenth and seventeenth centuries are notable for great progress in the use of gears and screws, and for substitution of positive mechanical action for movements produced by the weight of the apparatus or the muscles of the operative. In this period, the primary achievements lay in the construction of precision instruments (ch 23) and in light engineering. The obsession of the nineteenth-century writers with prime movers long obscured the

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[1] Franz Reuleaux, 'The Kinematics of Machinery'. London, 1876. (Translation of the German edition of 1875.)

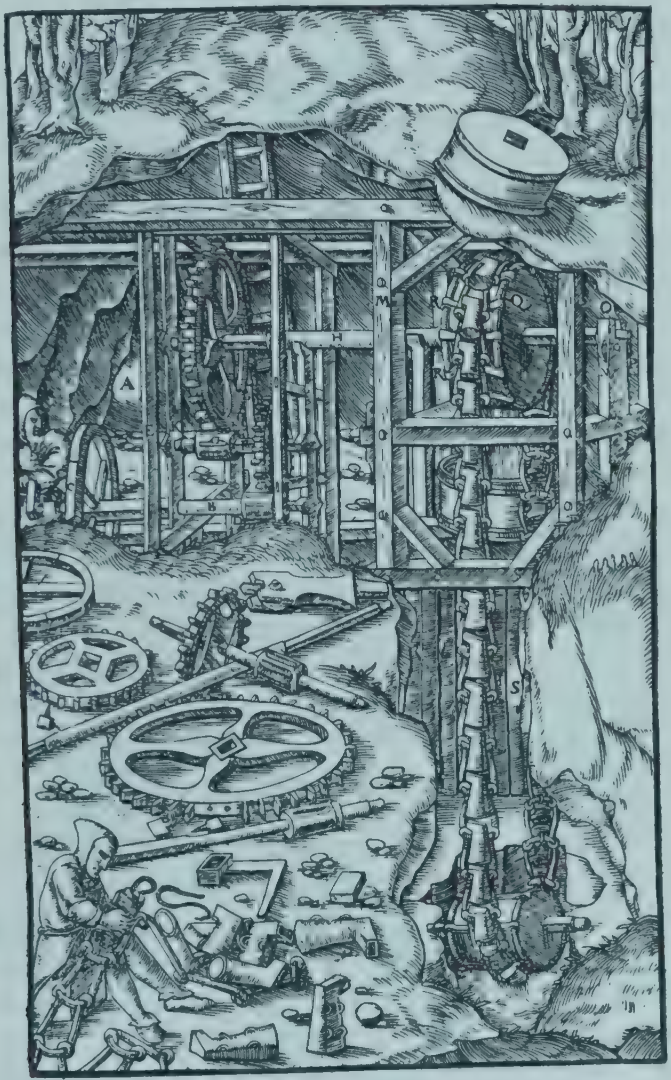

FIGURE 211—*Agricola's gear-operated chain-and-bucket pump. 1556.*

significance of the engineering and mechanical accomplishments of the sixteenth and seventeenth centuries, but a truer perspective has now been obtained and the earlier stages in technical development should be underestimated no longer.

Despite the great expansion of the iron industry, and the great increases in the skills of working and shaping metals, the use of metals in the construction of machinery proceeded very slowly. Here cost was more important than it was in making luxury goods or armaments, so that wood remained a basic material for machine-construction. Metals were used only for such parts of machines as required great strength or durability.

Agricola's description of the drive for a chain-of-buckets pump represents the most extensive use of iron in a sixteenth-century treatise (figure 211) [1].

> First of all [he writes] I will describe the machines which draw water by chains of dippers, of which there are three kinds. For the first, a frame [A] is made entirely of iron bars; it is two and one half feet high, likewise two and one half feet long, and in addition one sixth and one quarter of a digit long, one fourth and one twenty-fourth of a foot wide. In it there are three little horizontal iron axles, which revolve in bearings or wide pillows of steel [K], and also four iron wheels of which two are made with rundles and the same number are toothed. Outside the frame, around the lowest axle [B], is a wooden fly-wheel [C], so that it can be more readily turned, and inside the frame is a smaller drum [D] which is made of eight rundles, one sixth and one twenty-fourth of a foot long. Around the second axle [E], which does not project beyond the frame, and is therefore only two and a half feet and one twelfth and one-third part of a digit long, there is on one side a smaller toothed wheel [F], which has forty eight teeth, and on the other side a larger drum [G], which is surrounded by twelve rundles one quarter of a foot long. Around the third axle [H], which is one inch and one third thick, is a larger toothed wheel [I] projecting one foot from the axle in all directions, which has seventy-two teeth. The teeth of each wheel are fixed in with screws, whose threads are screwed into threads in the wheel, so that those teeth which are broken can be replaced by others; both the teeth and the rundles are steel. The upper axle projects beyond the frame, and is so skilfully mortised into the body of another axle that it has the appearance of being one; this axle proceeds through a frame made of beams [M] which stands around the shaft, into an iron fork set in a stout oak timber [N]; and turns on a roller made of pure steel [P]. Around this axle is a drum [Q] of the kind possessed by those machines which draw water by rag-and-chain; this drum has triple curved iron clamps [R], to which the links of an iron chain [S] hook themselves, so that a great weight cannot tear them away. These links are not whole like the links of other chains, but each one being curved in the upper part on each side catches the one which comes next, whereby it presents the appearance of a double chain.

The figure shows the details of the parts as well as the complete machine, but it is important to note its false scale. The man turning the crank would surely suggest a wheel of 5 or 6 ft in diameter on the main driving-shaft, though it is stated to be only 2 ft. The roller-bearings are noteworthy. There are sketches of such bearings in the notebooks of Leonardo da Vinci, but there are not many indications of their use at this date.

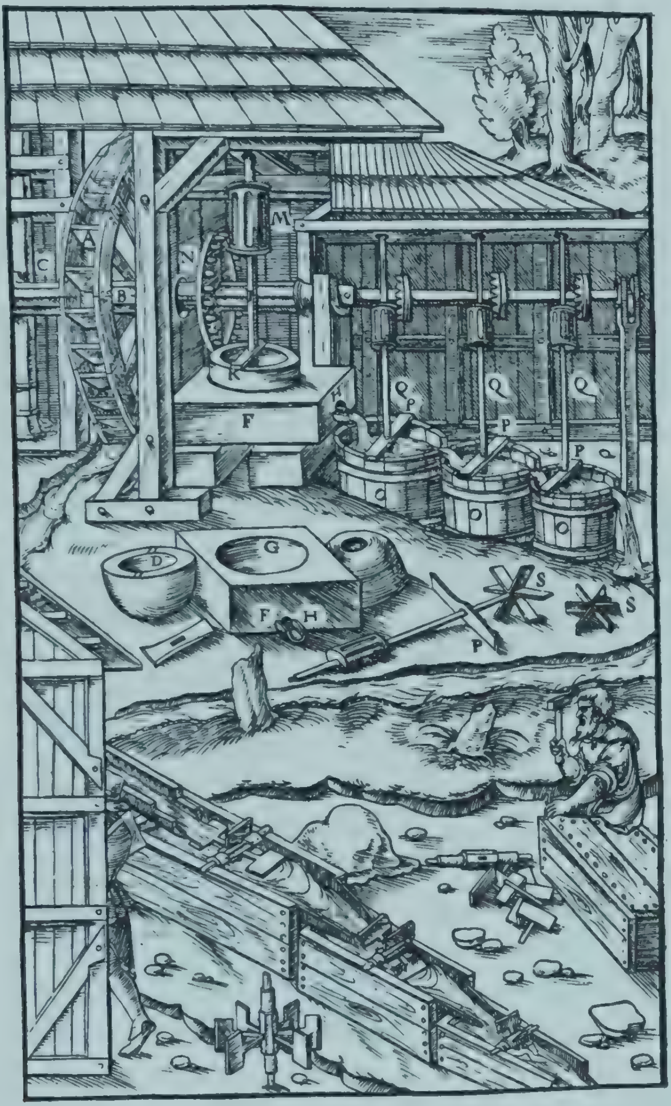

FIGURE 212—*Agricola's water-driven ore-crusher, mill, and mixer. 1556.*

A more characteristic mechanism is Agricola's water-driven ore-crusher, mill, and mixer designed for the mercury-amalgamation treatment of gold ores (vol II, p 42) (figure 212):

> This machine has one water-wheel [A], which is turned by a stream striking its buckets; the main axle [B] on one side of the water-wheel has long cams, which raise the stamps [C]

that crush the dry ore. Then the crushed ore is thrown into the hopper of the upper millstone [D], and gradually falling through the opening, is ground to powder. The lower millstone [F] is square, but has a round depression [G] in which the round, upper millstone turns, and it has an outlet [H] from which the powder falls into the first tub [O]. A vertical iron axle [I] is dove-tailed into a cross-piece [K], which is in turn fixed into the upper millstone; the upper pinion [M] of this axle is held in a bearing fixed in a beam; the drum of the vertical axle is made of rundles, and is turned by a toothed drum [N] on the main axle, and thus turns the millstone. The powder falls continually into the first tub, together with water, and from there runs into a second tub which is set lower down, and out of the second into a third, which is the lowest; from the third, it generally flows into a small trough hewn out of a tree trunk. Quicksilver is placed in each tub, across which is fixed a small plank [P] and through a hole in the middle of each plank there passes a small upright axle [Q], which is enlarged above the plank to prevent it from dropping into the tub lower than it should. At the lower end of the axle three sets of paddles [S] intersect, each made from two little boards fixed to the axle opposite each other [2].

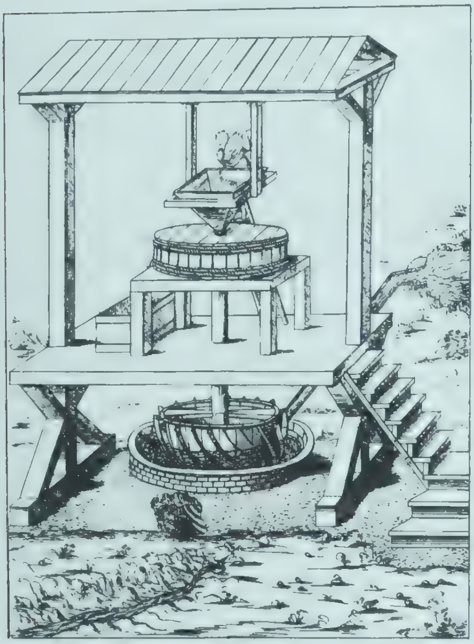

FIGURE 213—*Improved vertical water-mill described by Besson, making some use of the effect of reaction on the blades of the wheel, which are curved. 1579.*

The figure shows the general features of the wooden construction common in the treatise of Agricola and in his period. The water-wheel and the coarse-toothed wheels were common types. The loose engagement of the toothed wheels was centuries old, and continued with little change for two or three hundred years more. The train of gears for the chain-of-buckets previously described suggests a technique taken over from large clocks, whereas the machine shown in figure 212 is characteristic of the usual prime mover. It presents, however, an unusual feature in the drive-shaft with crown-wheels and lantern-pinions. From the eleventh and twelfth centuries onwards, shafts operating several devices commonly did so by means of tappets (vol II, pp 643–4).

There is little evidence of change in the design of construction of water-wheels and other machines using toothed wheels. The horizontal water-wheel without gearing, does, however, show an important new element. A new type is described by Jacques Besson (1579) as common in southern France (figure

213). This tub or pit-wheel introduced a new feature, which confined the stream and made more efficient use of the force exerted by the moving water on the vanes of the wheel. Thus the hydraulic action was more precisely controlled, not enough to make the wheel a true turbine, but enough to improve its performance [3]. This wheel, and other types that developed around Toulouse, undoubtedly set the stage for the invention of the water-turbine. The sixteenth century, however, worked with such loosely articulated machinery that a true turbine would have been inconceivable to the millwrights of the period.

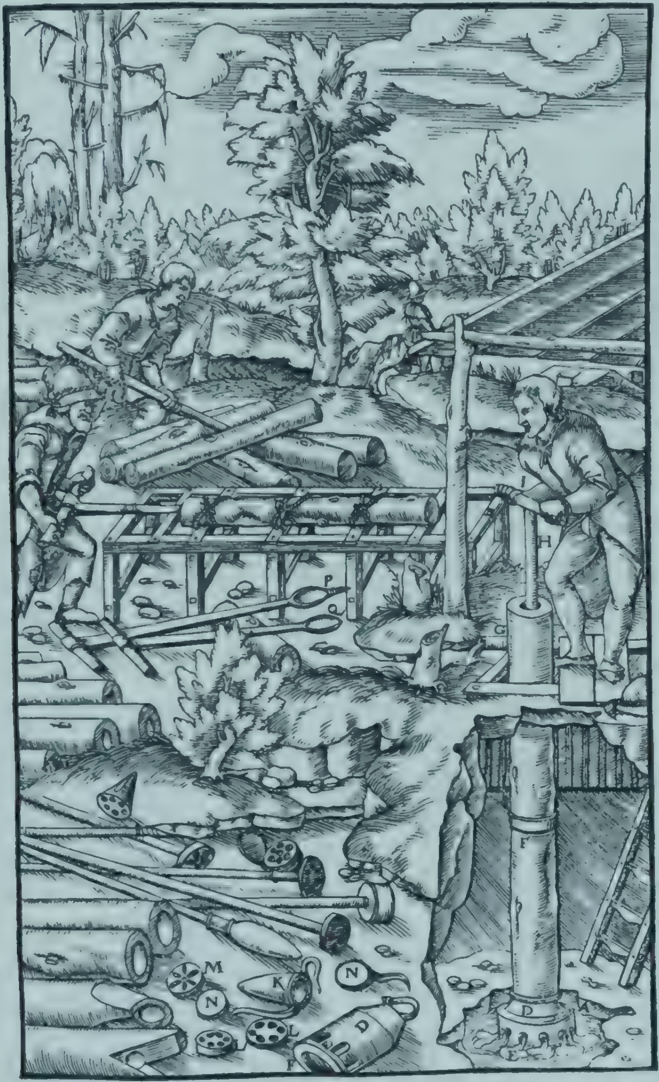

FIGURE 214—*Agricola's simple suction-pump. On the left a man is hollowing out tree-trunks, for pipes, with augers* (P, Q). *1556.*

The predominance of wood in the construction of mills is to be inferred from the plate in *Le diverse et artificiose machine* (Paris 1588), by Agostino Ramelli (1531–90), of the turret windmill for grinding grain. This is one of the earliest drawings of the turret windmill, though there is a rough sketch of this type in the notebooks of Leonardo. In his inadequate description, Ramelli states that the mill can be braked by the lever D, which tightens or releases a circular band in contact with a wheel on the main driving-axle of the mill (figure 47) [4].

After 1500 pumping machinery became much more important than during the Middle Ages. No new devices were invented, but many changes in design appeared. Mines and public or semi-public water-works required a progressive increase in the size of the installation. The prime movers involved little novelty of design or construction, whether water-, animal-, or man-power was used. The devices for raising the water reveal many advances in engineering as the suction-pump increased in importance in the sixteenth century. Even at an early date many parts of the pump were of metal, the use of lead, copper, and iron increasing steadily. In details of construction, as in its primary principle, the suction-pump laid the foundations for the steam-engine.

Agricola describes a simple form of suction-pump in which the use of metal was reduced to a minimum (figure 214). His description is particularly interesting because the construction of the piston and valves is shown in more detail than in other early drawings. This is the first of a group of seven suction-pumps.

> Over the sump is placed a flooring, through which a pipe—or two lengths of pipe, one of which is joined into the other—is [or are] let down to the bottom of the sump [A]; they are fastened with pointed iron clamps driven in straight on both sides, so that the pipes may remain fixed. The lower end of the lower pipe is enclosed in a trunk [D] two feet deep; this trunk, hollow like the pipe, stands at the bottom of the sump, but the lower opening of it is blocked with a round piece of wood; the trunk has perforations round about, through which water flows into it. If there is one length of pipe, then in the upper part of the trunk which has been hollowed out there is enclosed a box of iron, copper, or brass, one palm deep, but without a bottom, and a rounded valve [F] so tightly closes it that the water which has been drawn up by suction cannot run back: but if there are two lengths of pipe, the box is enclosed in the lower pipe at the point of junction. An opening or a spout [G] in the upper pipe reaches to the drain of the tunnel. Thus, the workman, eager at his labour, standing on the flooring boards, pushes the piston down into the pipe and draws it out again. At the top of the piston-rod [H] is a hand-bar [I] and the bottom is fixed in a shoe [K]: this is the name given to the leather covering which is almost cone-shaped, for it is so stitched that it is tight at the lower end, where it is fixed to the piston rod which it surrounds, but in the upper end where it draws the water it is wide open. Or else an iron disk [L, M] one digit thick is used, or one of wood six digits thick, each of which is far superior to the shoe. The disk is fixed by an iron key which penetrates through the bottom of the piston-rod, or it is screwed on to the

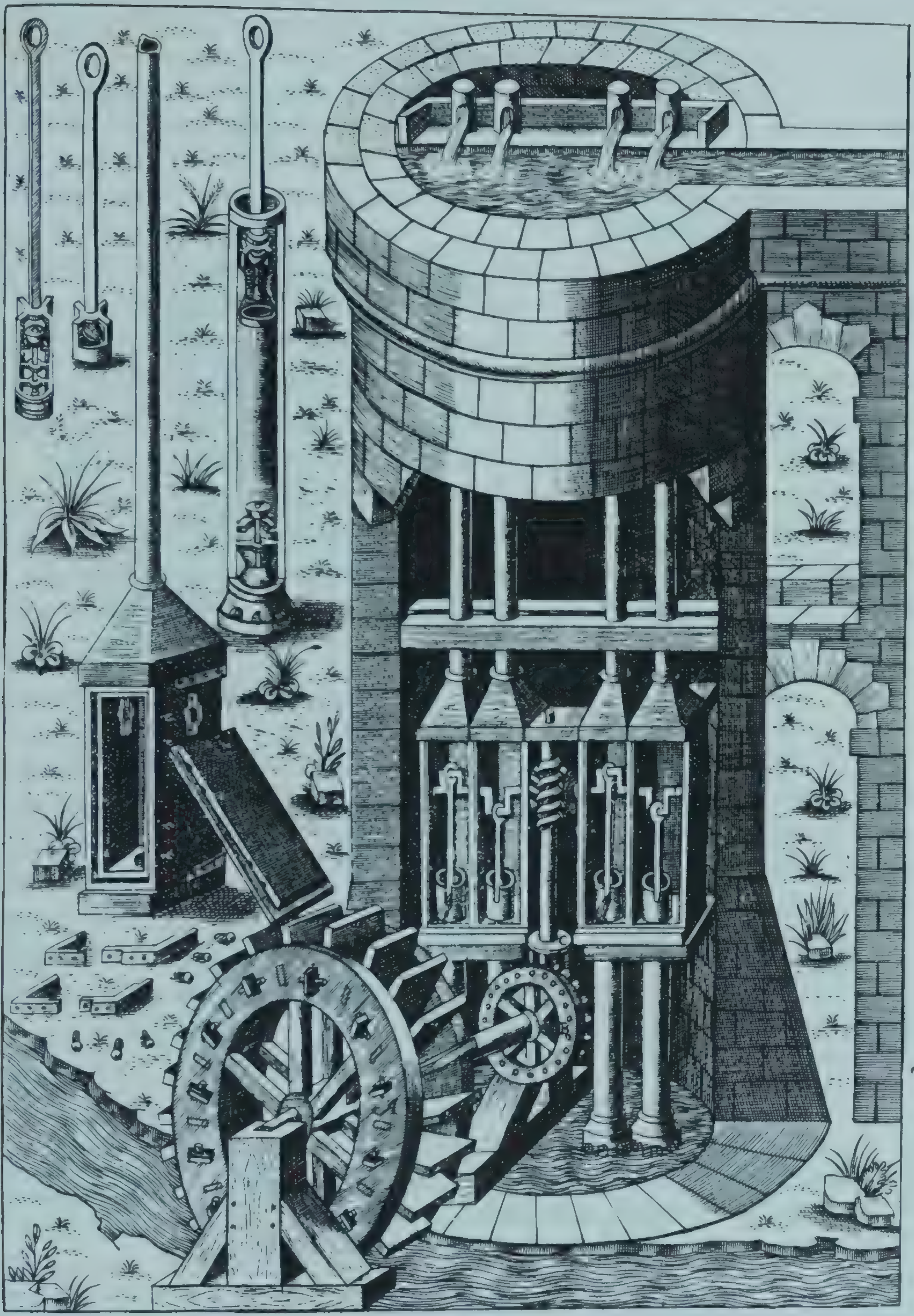

FIGURE 215—*Ramelli's quadruple suction-pump, 1588. Note the worm-drive. The insets show details of the valves.*

rod: it is round, with its upper part protected by a cover, and has five or six openings, either round or oval, which taken together present a star-like appearance; the disk has the same diameter as the inside of the pipe, so that it can be just drawn up and down in it. When the workman draws the piston up, the water which passed in at the openings of the disk, whose cover [N] is then closed, is raised to the hole or little spout, through which it flows away; then the valve of the box opens, and the water which has passed into the trunk is drawn up by suction and rises into the pipe, but when the workman pushes down the piston, the valve closes and allows the disk again to draw in the water [5].

The seventh of the series of suction-pumps consisted of a series of three pumps worked by a water-wheel 15 ft in diameter (vol II, figure 20). Each pump was composed of two 12-ft lengths of wood, with an inside diameter of 7 in. The piston-rods were 13 ft long and 3 inches in diameter. The valves were of the disk type described in connexion with the first pump. The driving-axle was iron, and a crank was used to convert rotary into reciprocating motion [6].

The fourth type of pump was distinctive because there were two pump-cylinders, which discharged into a tightly closed chamber with a single riser-pipe for outlet. The pistons were operated by manually turning a crank, which was connected to a double-throw crank-shaft of iron. The piston-rods also were of iron. This chamber is described as made of beech-wood, 5 ft long, 2 ft 6 in wide, and 1 ft 6 in thick. Because wood is likely to crack, the use of lead, copper, or brass is suggested [7].

This type of pump-action is shown in an elaborate drawing in Ramelli. A battery of four pumps is shown filling a cistern that serves an aqueduct. The valves are of a more advanced design than Agricola's, and there is a suggestion that metal be used for pipes, cylinders, axles, and pump-chambers. The description is, however, incomplete, and we therefore cannot be certain that this pump was constructed by Ramelli or in his time (figure 215) [8], but there can be no doubt that the suction-pump was extensively used, and its operation fully understood, almost a century before the scientific analysis of the vacuum by Galileo, Torricelli, and Pascal (*c* 1638–48). As the efficiency of the pump depended upon the tightness of the valves and piston, there was an evident advantage in the use of metal for pipes, valves, and cylinders. It would be tedious to follow in detail the progressive substitution of metals for wood in construction. It is enough to note that already in the second half of the seventeenth century cast iron pump-cylinders were employed, while copper and lead were widely used in pump-construction [9]. Pumps for domestic use were commonly made of lead, but the greater strength of copper made it desirable for larger installations. The general character of the engineering of this period is shown by Belidor's drawing of the pumping machine at the Pont Notre-Dame in Paris, which combined suction- and force-pumps (figure 216). The principal features are clearly evident in the drawing, notably the device for driving both pistons from one connexion with the power-shaft. The pump-cylinders were castings, but the metal is not named. In the reconstruction by Belidor in 1737 the principles were not modified, but the

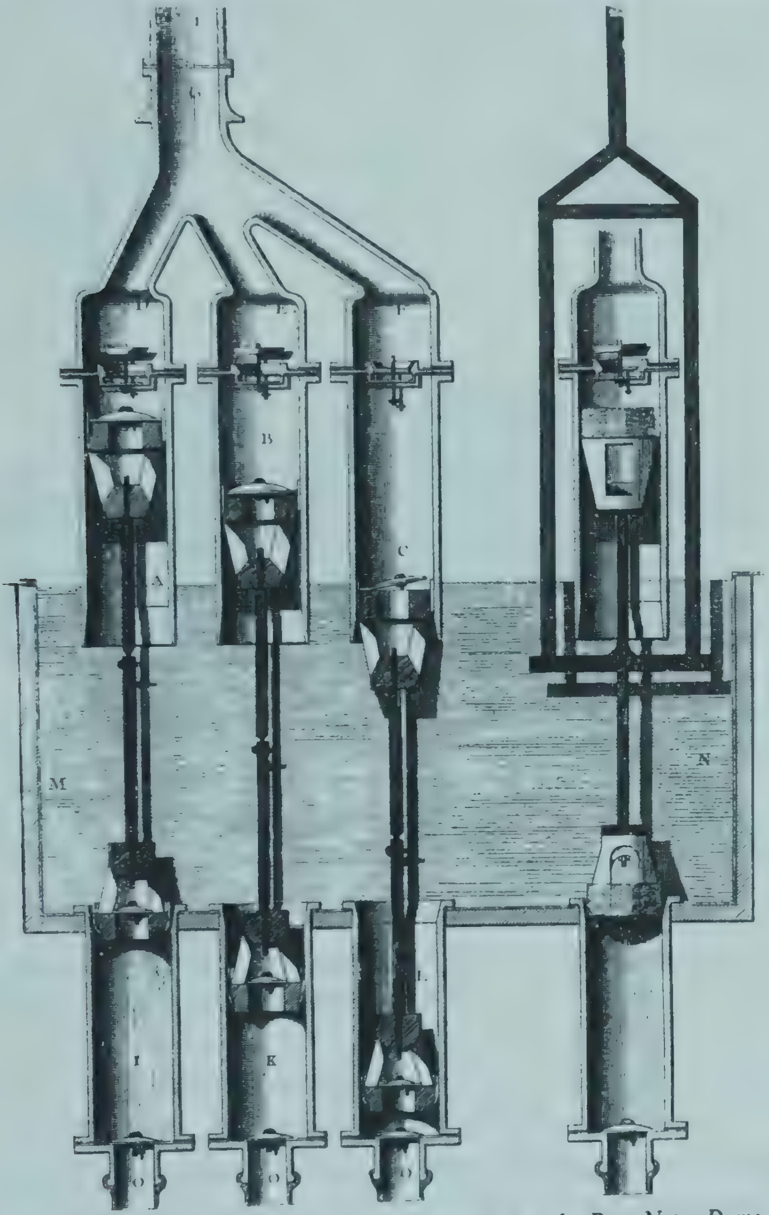

FIGURE 216—*Machine for raising water from the Seine installed at the Pont Notre-Dame, Paris, in 1670 and later reconstructed. The pumps were driven by a triple-throw crank rotated by a water-wheel turned by the river. Four sets of three pumps made up the whole machine.* (I, K, L) *Suction-pumps;* (A, B, C) *force-pumps;* (O, O, O) *supply-pipes rising 16 ft above the river;* (G) *pipe to hydrants.*

dimensions of cylinders and pipes were changed to provide for a better utilization of the capacity of the pumps. There were also revisions in the design of the pistons. Belidor's work is probably one of the most significant indications we have of the limits of engineering skills at this time, but it has as yet been too little studied.

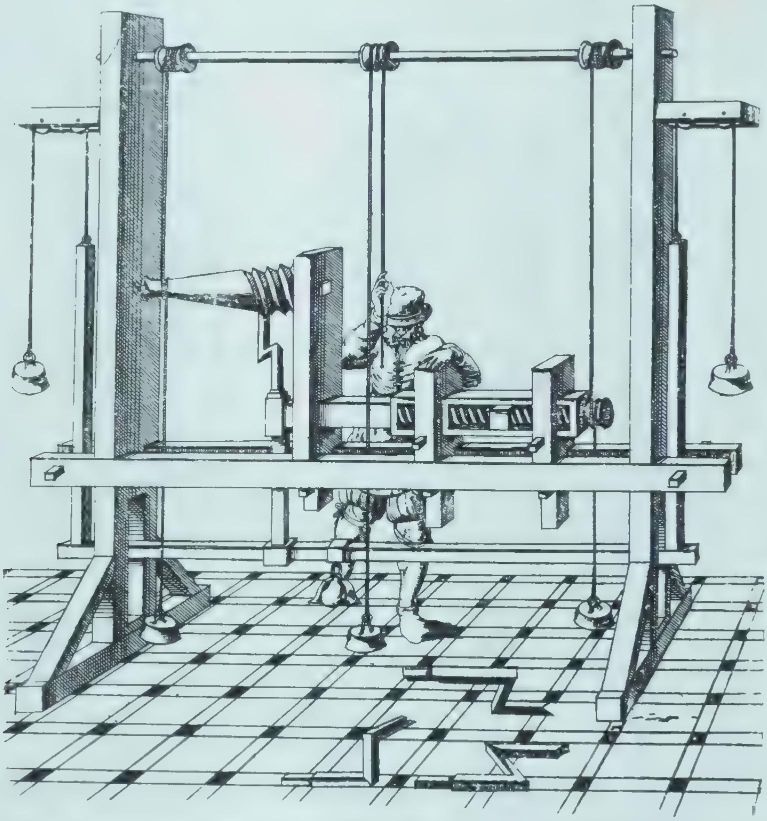

FIGURE 217—*Besson's screw-cutting lathe, 1579. The work is at the upper left. The curiously shaped tool is traversed by means of the long lead-screw* (centre). *Screw and work are both rotated by the high shaft and pulleys.*

II. THE SCREW AND ITS DEVELOPMENT

The development of light engineering and tool-making is closely associated with the extension of the use of the screw. The screw was well known in antiquity (vol II, pp 631–3), but its application was limited. Wooden screws were used in heavy-duty apparatus such as the olive-press, as well as in smaller devices for wine-making, compressing bales of cloth, and weight-lifting. The use of finer metal screws in instruments of precision was certainly suggested (p 610).

Although taps and dies were understood and are sketched by Hero of Alexandria, screws were made with the simplest hand-tools. The modern concept of the use of the screw in tool-making and machine-construction is first recorded by Leonardo da Vinci. In this respect, as in many others, it is not possible to determine the extent of his obligations to predecessors, but his work with the screw seems so far in advance of his time that we assume it to be original. His notebooks contain many sketches of long lead-screws used to control mechanical devices for reproducing the screw itself or for controlling cutting or shaping. The most important sketches show two schemes for reproducing a long lead-screw by mechanical devices. The first system shows a pole-driven lathe with a traversing-tool. The second system provides for more control of the cutting-tool. It is carried on a frame governed by two master screws, and cuts a thread on a blank spindle set between the master screws (vol II, figure 598). There is, therefore, clear evidence of a complete understanding of the basic principles of the use of a lead-screw. In this instance there are no grounds for presuming that Leonardo attempted to make such a machine. As sketched by him it would probably have proved too light even for cutting screws in wood.

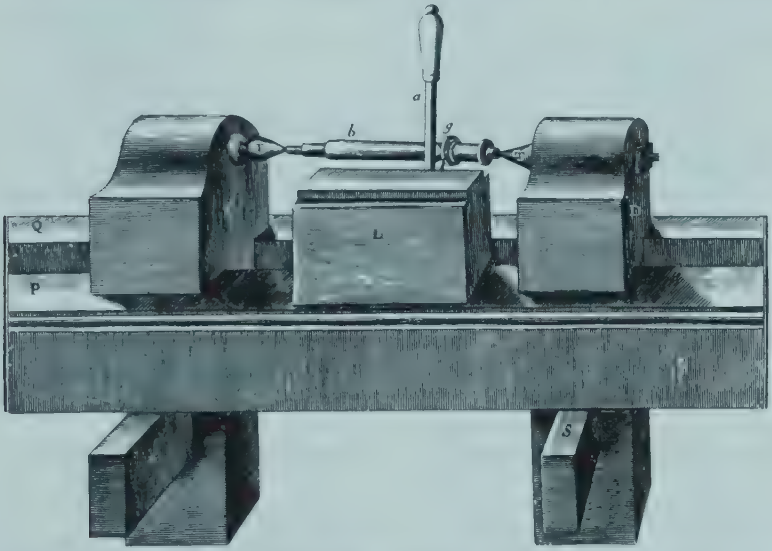

FIGURE 218—*Turning an iron mandrel on a lathe between puppets* (T, T). *The mandrel* (bg) *is rotated by means of a cord looped round it which is attached to a foot-treadle and a pole.* (a) *The cutting-tool;* (L) *the tool-rest.*

Besson illustrates a screw-cutting lathe with a long lead-screw and a traversing-tool (figure 217). The figure shows a piece of ornamental work in the lathe, but the construction would make it possible to reproduce the lead-screw. The oval-turning lathe of Besson was clearly intended for use in ornamental turning and need not occupy our attention.

Despite the adequacy of these machines in principle, they could not be used in practice, and long screws in wood or metal were cut with chisel or file, much as in antiquity. Short screws, both coarse and fine and in metal or wood, were commonly used for scientific purposes after 1650, for focusing microscopes and on many measuring instruments (ch 23). Long screws were, however, expensive and likely to be inaccurate. The use of a long lead-screw was obstructed by these difficulties in production. It is significant that lathe-work was developed on an alternative principle that presented less technical difficulty. The so-called mandrel-lathe was controlled by one or more short screws which gave the work a traverse of a few inches. Small pieces could be turned with the guidance of these screws supplemented by some form of fixed support for the cutting-tool.

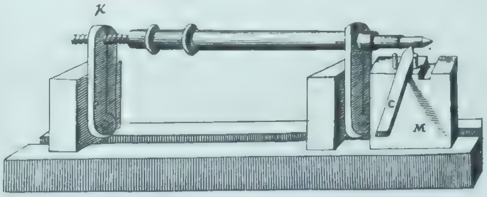

FIGURE 219—*Cutting the screw on the mandrel with the tool* C, *which is fixed by the pins in the block* M. *A guide-screw soldered into the end of the mandrel works in a female thread in the puppet* K; *thus the accuracy of the screw on the mandrel itself depends on the accuracy of the guide-screw.*

The mandrel-lathe is first recorded in a small engraving in Hartman Schopper's book on the crafts (1568) [10]. The engraving is too small to give any idea of the details of construction. It is difficult to trace the development of the lathe in the seventeenth century, before Plumier's detailed account of 1701 [11]. It was used principally for ornamental turning, but it embodied principles that were later to be of industrial significance, especially in clock- and watch-making.

In Plumier's time it was possible to cut the screws for the arbors of the mandrel on a lathe. Plumier was anxious to do so because it was difficult to produce a perfectly cylindrical mandrel with a file; but he found only two workmen in Europe capable of turning satisfactory mandrels in iron and steel. They used lathes of special construction firmly fixed between floor and ceiling and with some backing against the wall. A model of the mandrel was made in wood, somewhat larger in diameter than the finished article. The iron was first forged to this copy and turned to the shape required in the lathe (figure 218). A thread was then cut upon the end of the turned mandrel by the method shown in figure 219. The complete lathe is illustrated in figure 220. The same principle can be used in a centre-lathe, but Plumier gives no plate showing the general assembly of such a lathe. The production of screws by mechanical methods was thus severely limited. Techniques of casting should have been applicable to the production of screws in bronze. Cast iron would hardly have been satisfactory.

When these difficulties and costs of production are considered it is not easy to interpret the sketches of Besson and Ramelli, suggesting a wide application of heavy-duty screws to industry and construction. Yet examples survive to indicate that their ideas were not wholly visionary, though the elaborate decoration of the door-jack made at Nuremberg *c* 1570 (figure 221) suggests an article of luxury rather than an industrial appliance. The small screws used in scientific instruments and in bench-vices show the quality of craftsmen's skill that had been developed (plate 25) [12].

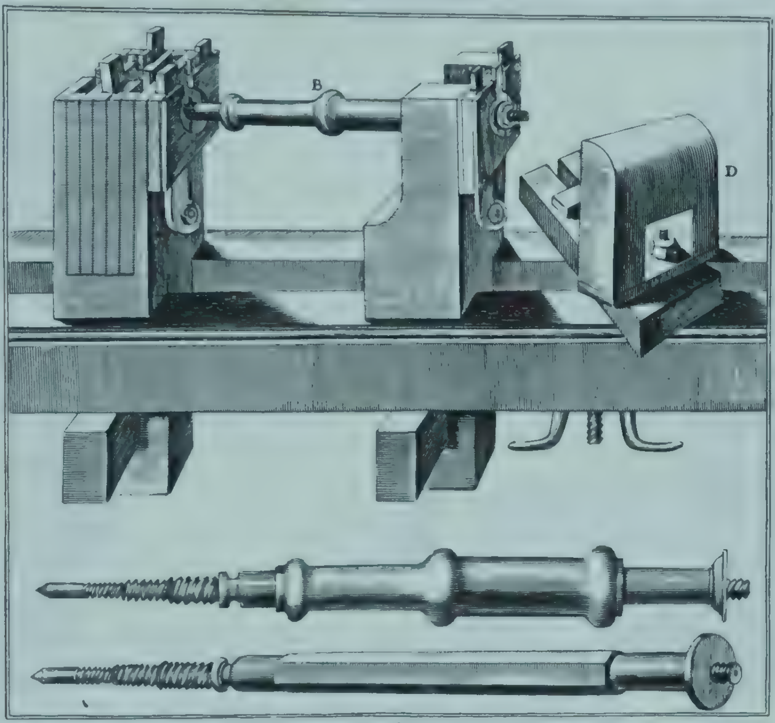

FIGURE 220—*The mandrel lathe complete. The traversing-screw on the mandrel engages in the left-hand puppet, so that it travels to and fro when rotated first in one direction and then in the other by a cord looped round at* B. *The cord is connected by one end to a treadle and by the other to a pole.* D *is the tool-rest. The frames of all these lathes were of wood. When continuous rotation was required a plain mandrel was used on which a pulley was mounted. An endless cord passed round this pulley and a large wheel turned by a crank.* (Below) *Two forms of mandrel with traversing-screws. Note short thread at the other end for attaching the work.*

New applications of the screw-press principle were made in printing and coinage. As is described below (p 382) the early printing-press was an adaptation of one of the lighter presses with a wooden screw, and it is first depicted in printers' devices (figure 250). About 1550, Danner of Nuremberg substituted copper for wood in the screw and secured finer impressions. Other details of the press are not primarily involved in the screw and its action.

The earliest use of a screw-press for die-stamping metals is attributed to Bramante. It is believed that he struck the lead seals of Pope Julius II (1503–13) with such a press. Medals, from dies engraved by Caradosso for Julius II, were also struck on a screw-press [13]. This new method of shaping precious metals, later extended to a wide variety of products, initiated a new type of quantity-production by die-stamping in powerful machines. Other forms of mechanized metal-working, such as rolling- and slitting-machines, are described below (p 342).

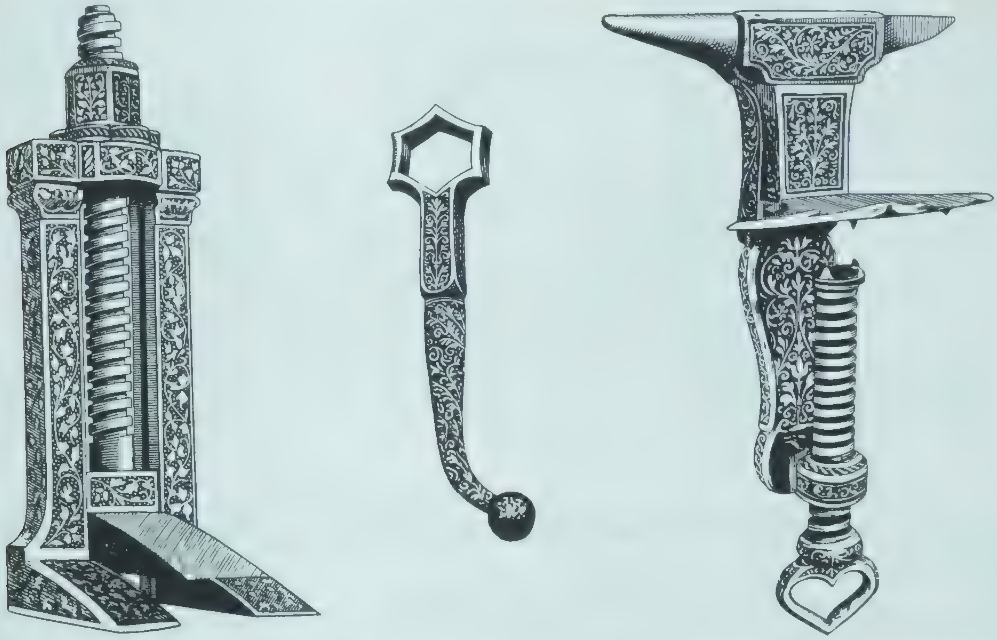

FIGURE 221—*Steel screws in engineering devices.* (Left) *Jack for lifting heavy doors, with contemporary spanner;* (right) *bench-vice with fixing-screw. Nuremberg work,* c *1570.*

We have no details of the construction of the first coinage presses. Cellini, however, describes a screw-press used by him to strike brass medals for Pope Clement VII (1523–34). Cellini's treatise on goldsmithery gives no drawing of the press, but figure 222 has been reconstructed from his description.

> Make a frame of iron as thick and wide as in the method previously described [two fingers thick and four wide] but so much longer as to admit, besides the two [square] dies on which the medal is cut in intaglio, the female screw of bronze which is cast upon the iron male screw.[1] This male screw is indeed what we commonly call a 'screw', and

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[1] The screw would be cut by hand, but there was no way of cutting the corresponding female thread directly in the iron frame. Therefore a separate bronze nut was made by direct casting on the screw, covering it with a mixture of ashes and fat and enclosing it in a suitable mould. The contraction of the metals would allow the screw to move in the nut after cooling.

> the female screw is called a 'nut'. The male screw should be made three fingers thick and its threads should be made [of] square [section], because they are stronger than those made in the other, ordinary way. The frame should be open at the top, and since the dies will be placed in it, and between the dies the metal to be stamped, it is necessary that the size of the nut be such that it does not shift in the frame. And because the dies have to be somewhat smaller, they are firmly fixed with iron wedges so that they do not move at all. Then have prepared a section of beam two *bracchia*[1] or more long, which is buried so that only half a *bracchio* remains above ground. This end is well planed. The lower end of the beam fits into a big piece of timber more than two *bracchia* long, while the frame is fitted into a slot in its upper end, into which [the frame] fits exactly. Then it is necessary to make clamps of strong iron, which strengthen the aforesaid beam where the screw [*read* frame] is fitted into it, so that it is not split.[2] The upper end of the screw is divided, and into this divided part is fitted a big ring of iron, which has two extensions that are pierced and fitted to a long pole, not less than 6 feet long. Then with four men dextrously holding the dies and the blank upright, [the latter] is stamped, which brings about the perfection of the medal. And in this way I struck for Pope Clement more than a hundred all of brass, without casting them, as I observed above is necessary when you choose to strike them like coins.[3] Finally the force of the screw is such when well considered that, although it is more costly and therefore renders this method of striking more expensive than the other way, it expends less money. Because, apart from the medals being better struck, the dies are less rapidly worn out; and, speaking of gold and silver [medals], I struck a great quantity without annealing any of them. In short medals are always properly stamped with two turns of the screw, whereas a hundred blows in ordinary coining would hardly have made one. Whence, for every one struck by the coiners, twenty are stamped with the screw; and of this enough has been said [14].

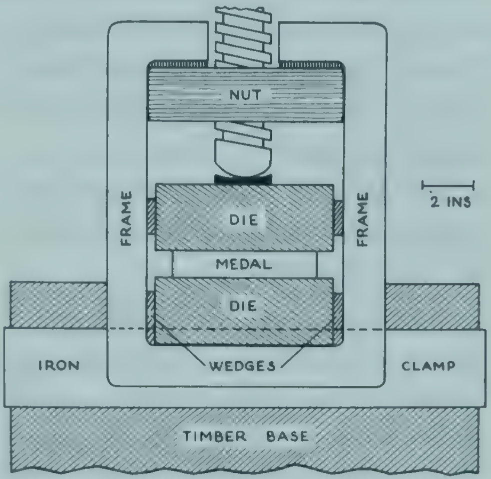

FIGURE 222—*Diagrammatic reconstruction of Cellini's screw-press for striking medals. The lower part of the timber foundation and the 'big ring of iron' (which was presumably attached to the screw in the horizontal plane) are omitted.*

Cellini's remark that the capital expenditure required to install a screw-press was heavy compared with that for the ordinary hand-coiner's equipment, and the fact that the coiners would lose their livelihood, may explain the resistance to the introduction of presses into mints.

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[1] A *bracchio* is about 18 inches.

[2] Apparently, bands of iron are fastened tightly round the upper part of the vertical beam, to prevent it from splitting through the torque exerted by the frame when the screw is forced round.

[3] Compare vol II, p 488.

III. BALANCE-PRESSES AND ROLLING-MILLS

The later form of balance-press is exemplified in the press of 1698 in the museum of the Hôtel des Monnaies, Paris (figure 223). The presses described by Abot de Bezinghen (1764) were of iron or bronze mounted on a heavy block of wood, marble, or cast iron. The lead balls at the ends of the balance will be noted. They varied with the length and weight of the bar. In the middle of the eighteenth century the heaviest weighed 150 lb each; the lightest 50 lb each. From other sources, we learn that these balance-presses weighed about 26 000 lb each. A press set up at the Royal Mint in London in 1651 weighed about 13 long tons.

The solidity of these presses was, of course, vital to their success. It may seem unjustifiable to classify such apparatus as light engineering, but the term can best be used to distinguish mechanisms operated by human or animal power from appliances driven by prime movers capable of exerting several horse-power. The balance-press was a truly elegant machine. With the weighted ends to store the energy used in swinging it, the minimum of power was required and none was wasted. It represented a high standard of mechanical design.

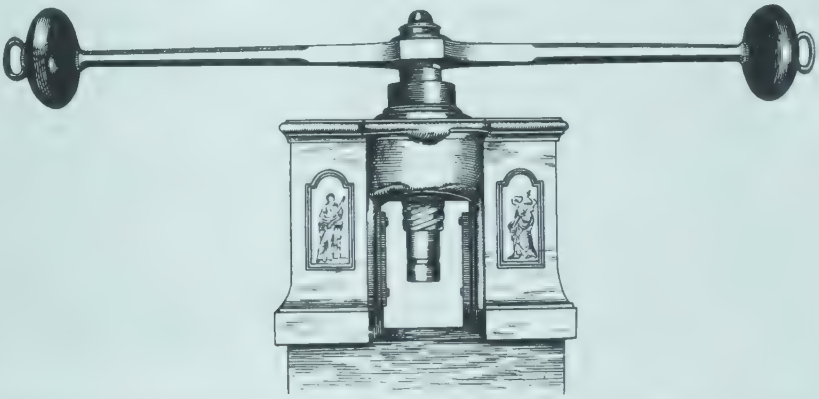
FIGURE 223—*Balance coining-press in the Museum of the Hôtel des Monnaies. 1698.*

The technique of working and shaping metals mechanically was closely associated with the development of coinage by machinery. Rolls and shears came into limited use in the working of copper and brass for other purposes, but the first major application of them is to be found in coinage machinery. The earliest sketches of rolls for working metals are in the notebooks of Leonardo da Vinci. Two devices are shown: relatively broad rolls for preparing sheet metal and narrow rolls for shaping staves [15].

In the second system the rolls were cut to produce a given profile on the staves. There was, therefore, a full awareness of the possible applications of these machines to metal-working. Curiously enough, the set of machines for coinage included a power-driven hammer for preparing the strips from which the blanks were to be cut. Leonardo sketched two types of punches for cutting blank coins, and an ingenious frame with a collar to direct a plunger against the die. Although he was associated with the mint in Rome at one time, there is no evidence that any of these devices were actually used.

The earliest applications of a new process of coinage occurred in France. Cellini had visited France in 1537, and a reform of the methods of coinage was discussed, but nothing was done. A new coinage was proposed in 1548 under Henri II and, on the suggestion of the French ambassador in Austria, mint machinery was purchased from Max Schwab, a goldsmith of Augsburg. There were rolls for reducing the cast plates or bars to proper thickness; draw-benches to adjust the thickness of the rolled product; circular punches for making blanks; balance-presses for striking the coins; and tongs, or appliances for holding the dies under the press [16]. The machines were set up in the Palais du Louvre in January 1552. The *Cour des Monnaies* opposed this project, but coins were produced at the Louvre until 1585, when the *Cour des Monnaies* succeeded in restricting the manufacture at the Louvre to medals and copper. Despite these restrictions on its activity, the technique was perfected and in continuous use.

A different method of using rolls for coinage came into use at Hall (now Solbad Hall) in the Tyrol about 1575. The prepared strips of gold or silver were passed between engraved rolls, which impressed the design on the strips. The coins were then cut out of the strips by punches, and finished. This process was brought to Spain and set up at Segovia, because there was no adequate water-power in Madrid. A somewhat similar process was developed by Nicholas Briot and used in the Scottish mint in 1639. The designs were engraved on portions of two cylinders, which did not make a full revolution. The blanks were made oval, but became round in passing through the rolls [17]. We must, therefore, presume that the Tyrolese system was not likely to rival the balance-press introduced in France with the rolls for preparing the blanks.

The power-driven rolls of the French system were introduced into England in 1561, but the French workman, Mestrell, was condemned to death for counterfeiting. No subsequent use of the rolling-mill for the English coinage can be ascertained before Peter Blondeau was brought over from Paris in 1649. In 1651 he was authorized to issue coins in collaboration with Thomas Simon, the engraver of the Mint. Blondeau added to the equipment of the French system a device for marking the edges of the coins with an incised or raised motto, or with serrations. Coinage began in 1657–8 [18].

The application of rolls to working copper and lead cannot be traced with any assurance in the period immediately following Leonardo's time, nor do we know how the practices he described were related to the techniques current in his time (p 47 and figure 19). The treatises of Zonca (1607), de Caus (1615), and Branca (1629) describe applications of the rolling-mill on a small scale to gold, silver, copper, and lead. These descriptions, however, are of no great importance as rolls were already established in the mints, and early applications to iron-working were described by Esban Hesse in 1532. Rolls were also used for preparatory processes by the wire-drawers and nail-makers of Nuremberg. In the earliest account there is no clear reference to flat rolls; a sheet already prepared was passed through a series of cutting-rolls which produced small bands suitable for drawing. Later, flat rolls were used to give greater uniformity to sheet iron [19].

We have little detail on the use of rolls in the seventeenth century, though it is implied that black sheets for tinning were rolled in Saxony in that period. Substantial information is first available in the 'Political Testament' (1746) of Christopher Polhem (Polhammer) which describes methods of iron-working that can be safely carried back to the beginnings of the century. After a long association with iron- and copper-mining as engineer, director of the mines at Falun, and member of the Swedish commission on mines, he established a manufactory for iron and other metal products at Stjärnsund, about 1704. The works produced a wide array of iron and steel products for industry, agriculture, and general consumption. Copper, bronze, tin, and lead were also worked up. Tinned sheets and articles made from them were especially important [20]. The underlying conception of the establishment was the utilization of water-power wherever possible, even though supplementary manual labour was necessary for finishing processes. There was, therefore, a deliberate and planned division of the processes of manufacture, sometimes using different mechanisms for different stages of the process, sometimes employing machinery and manual work in succession. The works were operated continuously until after Polhem's death in 1751. They were destroyed by fire some years later, and never rebuilt. These new techniques of production exerted an important influence in Sweden and elsewhere. They represent the highest level of accomplishment of an iron industry based on charcoal, and dependent for primary power on water-wheels and horse-driven gins. Unfortunately, Polhem's 'Political Testament' is not illustrated, but many models of his machinery are preserved in the museum of the commission already mentioned.

The machinery at Stjärnsund was of two kinds—hammers and rolls. The hammers, even when worked by power, represent the older technique. The rolls were an advance over contemporary methods of metal-working. According to the water-power available, it was possible to produce on the rolls ten or twenty times as much band iron as could be finished under the hammers. Rolls could be designed to turn out rough knife-blades to be cut apart and finished by the blade-smiths. With the rolls, all kinds of rods and bars were made—square, round, or half-round—as well as strips of steel for files. Sheets were rolled for plates and dishes, and for a variety of tin wares [21]. Polhem was not alone in using rolls for these purposes, but he says that hammers were more commonly employed and that the number of rolls in Sweden was small. This he ascribed to the difficulty of making them.

This process, invented in 1737 and first used in the mint at Cassel, is described carefully in the 'Political Testament'.

> All kinds of the smaller rolls up to six or seven inches in diameter can be easily forged out of good iron. The surface is hardened by applying a layer of steel which is welded on and forged. The rolls are then turned on a lathe driven by a small water-wheel. The cutting tool is fastened in a block which is drawn down the length of the lathe by a long screw. This is commonly done by the hand of the turner, but the machine can be arranged so that the water-wheel turns the screw. When the rolls have been turned on the lathe, they are placed in a lathe without traverse which is turned by a wheel. In this lathe they are corrected with small tools and files so that they are round and smooth. They are then tempered. . . . After being tempered the rolls are put back in the lathe and tested to see if they are still as round as they were before, which rarely happens. It may well be that the steel is thinner in some places than in others, so that in cooling the side where the steel is thinnest contracts more. If the rolls are also not defective because they have laminated, which can easily happen in the course of tempering, one proceeds to polish them. This is done by passing a band around the roll and polishing it under a tin or leaden cover with coarse and later fine emery until it is smooth and round [22].

There is a brief reference to the problems of rolling roofing-sheets, and the 'Political Testament' then proceeds with a description of the use of cast iron rolls and of the process of casting them.Polhem also gives directions for making rolls of malleable iron, which were specially treated to make tin-plate.

The whole account is rich in its implications. The general understanding of the use of rolls was not new, but Polhem was doing many new things with them: partly because of his more vivid vision of the advantages of a less direct process of production, partly because his versatility as an engineer made it possible for him to achieve new results by better methods of machine construction. The successful solution of engineering problems is essential if effect is to be given to new modes of motion and new compositions of the elements of mechanisms. Polhem's work provides a fresh standard for measuring the technical accomplishment of the first generation of the eighteenth century. To attain any complete knowledge of the history of technology it is essential to understand the nature of the achievement of such practical engineers of the age before the great industrial revolution as Belidor and Polhem, who prepared the way for its far-reaching economic and social changes. Polhem was an inventor of great fertility of imagination, as well as an engineer of distinction. It is a strange caprice of history that he is so little known.[1]

IV. SCIENCE AND THE ENGINEER

It is important to emphasize the close interweaving of engineering as an empirical practice with science as a systematic investigation of general principles occurring in this period. The sixteenth and seventeenth centuries mark the transition from complete empiricism to engineering techniques fully grounded in mathematics and applied science. Leonardo made great advances in the rigorous analysis of problems of dynamics, and his work was carried to a high level of achievement by the great figures of the seventeenth century, particularly Galileo, Huygens, and Newton. Scientific work was sometimes closely related to practical problems of engineering. The analysis of the vacuum by Galileo, Torricelli, and Pascal was directly inspired by the extending use of the suction-pump. Their results led directly to the study of steam and to the atmospheric steam-engine.

Special problems of dynamics were encountered in the development of clocks and watches (ch 24). Analysis of the properties of the pendulum and of the balance-spring resulted in notable improvements in their performance. These discoveries were not empirical achievements, but the result of the application of mathematics to the study of dynamics begun by Galileo and continued by Huygens and Newton. Increased interest in the determination of longitude by accurate measurement of time rendered the improvement of clocks a question of practical as well as scientific importance, and prevented complacent acceptance of standards that fell short of the precision required in astronomical work.

In the analysis of the pendulum there is an interesting point which illustrates the fact that the attainment of theoretical perfection in a device may not be essential to its practical success. At an early date Huygens recognized that though the pendulum is not (as Galileo had supposed) perfectly isochronous when swinging in circular arcs, the errors introduced are negligible if the arc is small. In his rare work *Horologium* (1658) he described a clock in which the circular error was so reduced by making the pendulum swing through only a few degrees. It was not until the end of 1659 that he discovered that oscillation in a cycloidal arc is invariably isochronous, irrespective of its amplitude. From this time, influenced partly by the elegance of his mathematical discovery and partly by his belief that pendulums with a large swing would keep time more accurately at sea, he constructed his clocks in such a way that the pendulum traversed a wide cycloidal arc. Although Huygens's work on the cycloid marks an important contribution to dynamical theory, his earlier observation was more significant for practical clock-making. All practical pendulum clocks since then have used a pendulum swinging in a short circular arc, and the cycloidal cheeks devised by Huygens were never generally adopted; they are indeed quite unnecessary complications.

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[1] For an account of his life (1661–1751), see *Nouvelle Biographie Universelle* (1852–66).

The introduction of the pendulum, which increased the accuracy of time-keeping at least tenfold, gave a great impetus to the attempt to improve the mechanics of the clock, by cutting gear-teeth more precisely and to the most efficient profile, and by devising new escapements, such as the anchor and dead-beat types (pp 665, 671), which would enable the pendulum to oscillate with as little disturbance from the drive as possible. The superiority of epicycloidal teeth was first shown by Roemer and Huygens in 1674 and 1675, their results being communicated to the Académie des Sciences in Paris. Huygens continued the investigation with a study of the form of teeth for crown wheels in 1680. Further studies in this field were made by Camus in 1735, and Thiout in 1741.

The attempt to examine the action and shape of gear-wheel teeth scientifically was, however, limited to the light trains of clocks and watches. Here much advance took place, but it was almost without effect on the design of heavy-duty gears, for example in millwrights' work. In this respect, as in others already discussed (accurate machining of parts by use of the lathe, use of the screw, and so forth), small-scale light engineering led the way towards higher standards of craftsmanship and design. The skill, the machine-tools, and the economic incentive were as yet lacking in the early eighteenth century to transfer to manufacturing machinery the precision and complexity already found in scientific instruments, clocks, and watches; but the basic principles required were at hand, and fully worked out on this small scale.

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[5] Agricola, Georgius. See ref. [1], p. 176.

[6] *Idem. Ibid.*, pp. 184–5.

[7] *Idem. Ibid.*, pp. 179–81.

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[14] Cellini, Benvenuto. Opere, Vol. 3, pp. 109–11. Milan. 1811. The quotation on pp. 338–9 translated and the figure reconstructed by A. R. Hall.

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[16] Hocking, W. J. See ref. [13], pp. 68–69.

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[20] *Idem. Ibid.*, Vol. 3, pp. 1101–4. 1897.
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14

MILITARY TECHNOLOGY

A. R. HALL

I. STRATEGY AND TACTICS

DURING the sixteenth and seventeenth centuries there was no such violent revolution in the art of war as the invention of gunpowder had wrought in the Middle Ages (vol II, pp 374–82, 726–7). The consequences of that revolution had begun to be of considerable effect during the fifteenth century and were carried progressively farther during the present period until a new position of stability was attained towards its close. Thereafter, though there was a great improvement in the organization of military forces, and a large increase in their size, there was little further change in weapons or the methods of their manufacture for some 150–200 years. The flint-lock musket, the muzzle-loading smooth-bore gun, and common black powder remained the principal destructive agents until well after the Napoleonic wars; only about the middle of the nineteenth century were they rendered obsolete by advances in metallurgy, engineering practice, and chemistry.

Hand-guns and field- and siege-artillery were already prominent in war before 1500. The only major innovation of the next two centuries was the extensive use of explosive projectiles in the form of hand-grenades and mortar-bombs, weapons rarely employed in the fifteenth century and having their greatest scope in the elaborate siege-operations of the seventeenth. But the problem of utilizing fire-arms in the field had not been satisfactorily solved by medieval armies. The administrative problems ranged from high questions of national policy, such as the establishment of powder-works and the control of the armaments industry, to the mobility of artillery in the field and the provision of different kinds of powder, ball, and match. Armies became far more dependent on the organization of their baggage-trains and lines of supply than formerly. By the end of the seventeenth century these matters had been settled as well as the transport and other means of the time allowed—as one may see, for example, from Marlborough's long march before Blenheim (1704). The manufacture of arms was carefully supervised by the state, or even conducted in its own establishments, and facilities for experimentation and inspection had been created. Large quantities of cannon and ammunition could be moved as the commander required, specialist corps of engineers and artillerymen had been formed, and logistics played an important part in the preparation for actual operations.

Thus the greater technical complexity of war stimulated both the growth in power of the state and the enforcement of stern discipline and training within its armed forces. The impetuousness of feudal chivalry had indeed been checked by English archers in the fourteenth century and Swiss pikemen in the fifteenth, but the new weapons demanded high precision in the performance of routine operations, and absolute steadiness at moments when the infantryman or gunner with a discharged piece might seem defenceless in face of an enemy onslaught. For the rate of fire of early guns was very slow, and the hand-gunner especially had to become perfect in the elaborate sequence of motions involved in the loading and firing of his weapon: all modern military drill derives essentially from this fact.

Throughout the period, infantry were divided in their defensive and offensive functions, the pikeman providing the former and the hand-gunner the latter. Various tactical formations were adopted to enable arquebusiers or musketeers to bring their weapons into play while sheltering behind pikes which protected them from enemy cavalry, this enforced combination of arms itself enhancing the need for parade-ground precision in movement and obedience to orders [1]. Only towards the end of the seventeenth century was the solution to this tactical problem discovered, in the attachment to the musket of a bayonet which, without impeding the firing of the piece, rendered it nearly as effective in defence or a charge as the true pike. About the same time, too, the cartridge was introduced, a paper packet containing a measured charge of powder and a ball, so that the operation of loading the musket was simplified and made more rapid.

There are pictures of horsemen carrying hand-guns in the fifteenth century, but the weapon could hardly have been effective in the hands of cavalry before the invention of the wheel-lock pistol (p 355). Thereafter cavalry, like infantry, divided into two classes: those equipped with piercing or slashing weapons (lances and sabres), and those equipped with fire-arms. They had correspondingly different functions, the former being mainly used to destroy a broken or disorderly formation, and the latter acting as mobile musketeers. The tendency for the horseman to lose the pre-eminence he had enjoyed in the earlier Middle Ages, already apparent before gunpowder played a serious role in war, was certainly fortified by the new invention. At the beginning of the sixteenth century the most formidable fighting force in Europe was the Spanish infantry (as the Swiss pikemen had been previously), and military writers pay far more attention to the tactical management of infantry than to that of cavalry. The first half of the next century, however, saw a succession of great cavalry leaders (Maurice of Nassau, Gustavus Adolphus, and Oliver Cromwell especially) who learnt how to combine the impetus of a charge with a deliberate volley from heavy pistols, and to exploit thereby the weaknesses of unmounted troops. In the wars of Louis XIV's reign, the foot-soldier recovered his position with improved weapons and more effective support from field-artillery, while the restriction of mobility by prolonged sieges allowed fewer opportunities for the horseman's dash. Nevertheless, this still had its important place in open warfare until less than a century ago.

Strategy was dominated by three considerations: the desire to bring about or avoid a pitched battle between two armies, destroying the enemy force or preserving one's own; the need to secure lines of communication and, for many states, open avenues between their geographically scattered territories; and the ambition to occupy the enemy's seat of government. From the later stages of the Hundred Years War to Charles VIII's invasion of Italy in 1494 with what was perhaps the first 'modern' army, excellently equipped with artillery, wars had been fought on a minor scale: the Wars of the Roses (1455–85) in England were hardly more than a series of skirmishes, and in Italy fighting was carried out by mercenaries who so arranged matters that battles were decided without much bloodshed.

In the Italian wars between France and Spain in the early sixteenth century, however, the vital issue was the occupation or effective control of Rome and the chief cities; hence war became more bitter as the rival forces sought each other's complete destruction. The same is still more true of the Wars of Religion (*c* 1540–1648), which were for the most part civil wars involving each religious party in the ambition to secure complete dominion over its opponents. The revolt of the Spanish provinces in the Netherlands (1566–1609) and the Thirty Years War (1618–48) in Germany both show concentrated attention devoted to the technical improvement of arms and fortification, widespread destruction of towns and civilian population, and a growing realization of the significance of economic considerations in determining strategy. As religious fanaticism declined, commercial rivalry took its place, with the Dutch as the main object first of English, and later of French envy; and European wars were now regularly extended to the colonial possessions of combatant powers. For a number of reasons, including the perfection of means of fortification, continental warfare was restricted in violence, moving—apart from the occasional brilliance of such a commander as Marlborough—from siege to leisurely siege. Victories costly in human life, like that of Malplaquet (1709), were avoided by prudent generals.

Something should be said of naval warfare, since the invention of artillery opened the possibility for completely new tactics. In early naval battles a ship might be lost through boarding and capture (the method preferred by the Romans), by ramming, or by the use of incendiary compositions such as 'Greek fire' (vol II, p 375). With cannon it was possible to batter a vessel into an unnavigable wreck, to sink it by shot below the water-line, and not infrequently to blow it up by the explosion of its own magazine of powder. Such tactics, relying on bombardment from very heavy guns, were apparently first fully exploited by English sailors, classically against the Spanish Armada in 1588. Before this, naval commanders had rather aimed at weakening the crews of enemy vessels by light cannon and small shot in preparation for boarding, as at the famous battle of Lepanto (1571); but the numerous small guns and large crews of the Armada were never able to take an effective part in that action. Broadside tactics were paramount in naval battles until after the time of Nelson; ships were little more than platforms for increasingly more massive cannon, and the issue was decided by weight of round-shot delivered at point-blank range. Cannon of the size mounted on the lower decks of first-rate men-of-war were almost immovable on land; hence it was from the sea that the demand came to the foundries for ever weightier and stronger castings.

II. WEAPONS (OTHER THAN FIRE-ARMS) AND ARMOUR

There was little alteration in the art of the smith, and it may well be that the sword-steel of early modern times was inferior in quality to that of the famous blades of Damascus and Toledo. The temper of steel weapons and armour was no longer such a critical matter as it had been in the past. In northern Europe there was some substitution of coal for charcoal in the smith's forge, and his material—bar iron—was wrought for him by water-driven hammers and, later, rolling-mills. It was not yet possible to smelt iron-ore with coal, to roll iron plate, or to make and work steel in large quantities. Weapons and armour were forged by traditional hand-work methods without the aid of power, though Stradanus shows armour being polished by water-driven machinery (figure 224).

Of the types of steel weapons little need be said. The sword with all its variants—claymore, cutlass, sabre, rapier—remained an important arm in the sixteenth and seventeenth centuries and was still carried by pikemen, for hand-to-hand fighting occurred in all serious battles; but by 1750 it had become little more than a symbol of gentility. Apart from the cavalry sabre emphasis tended to be placed on play with the point rather than on slashing strokes: thus the sword became lighter and more flexible. The hilts of special weapons were elaborated with decorative work. Axe-like weapons, such as the halberd, were soon restricted to ceremonial uses. The long, heavy lance of the medieval knight disappeared, to be replaced by a lighter and shorter weapon retained only by some groups of cavalry. The main arm of the infantry was the pike, a stout shaft 12–18 ft long with a steel head (figure 226), gripped in both hands and presented almost horizontally. It was a clumsy but effective weapon, pre-eminent in days of slow small-arms fire in resisting a determined attack of cavalry.

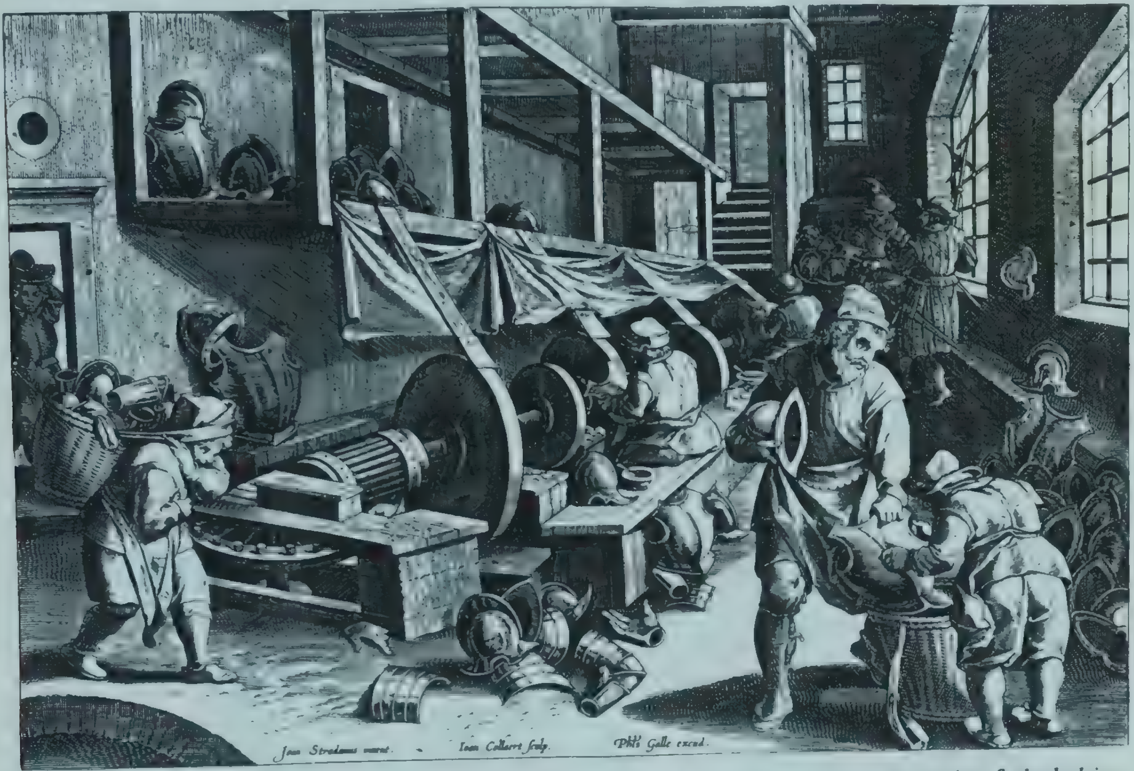
Joan Stradanus invent.
Ioan Collaert sculp.
Phls Galle excud.

FIGURE 224—*Sixteenth-century armourer's workshop: the armour is ground and polished on a series of wheels driven through gearing by water- or animal-power. An attempt is made to prevent the workers from having to inhale metallic dust. From a copper-plate,* c *1590.*

Although corps of hand-gunners had been raised about the middle of the fifteenth century, and the bow was obsolescent in war by about 1500, it was still considered as a serious weapon for another hundred years. The best-known work on archery, Roger Ascham's *Toxophilus*, was published in 1545, and the Artillery Company which received a charter from Henry VIII in 1538 was originally composed of archers. In England proclamations encouraging the use of the long-bow were issued as late as 1633, but by this time archery had become no more than a sport. The bowman of Elizabeth's reign was supposed to carry eight light arrows among the twenty-four in his leather quiver 'defensible against the rayne', in order to 'gall or astoyne the enemye . . . before they shall come within the danger of harquebuss shot'. Each bowman was equipped with a 'little cote of plate', a steel cap, 'a mawle of leade five foote in lengthe', and a dagger. In the hands of skilled archers the English long-bow was greatly superior in rate of fire to the primitive hand-gun, and probably equal to it in accuracy and

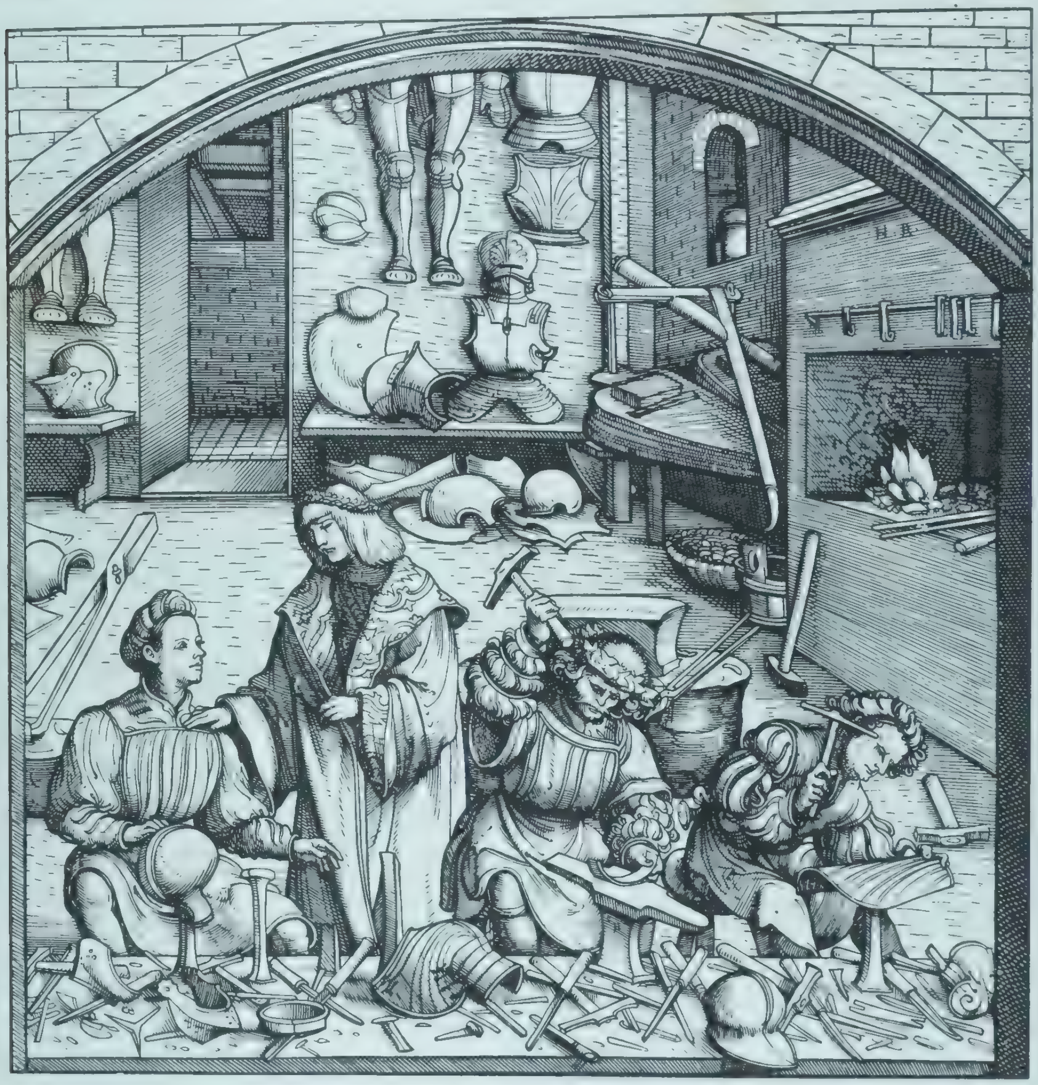

FIGURE 225—*Early sixteenth-century armourer's workshop, probably depicting a visit from Maximilian I to Seusenhofer. Forge with bellows on right, complete parts of fluted armour in background. Note the armourer's variety of anvil-stakes, hammers and files, and the large shears.*

effective range, yet lacking the 'stopping-power' of a heavy ball, especially against armoured men. The cross-bow, which also survived into the sixteenth century, disappeared from war even more rapidly than the long-bow. As an expensive weapon, in whose use men needed careful training, with a poor rate of fire, it had even fewer advantages in comparison with fire-arms. It still found favour in hunting, however, many of the finest examples in museums being made well after 1550; the 'prodd', a type shooting small stones or pellets and used chiefly for fowling, remained fairly common until the end of the seventeenth century.

Armour was virtually laid aside by the end of this period, save for display, though the armourer in his losing battle with fire-arms had continued to produce pistol- and musket-proof plate into the early seventeenth century. The zenith of his craft had been reached about a hundred years earlier, notably in the 'Maximilian' or fluted armour said to have been invented by Conrad Seusenhofer, armourer to the Emperor Maximilian I (r 1486–1519) (figure 225). Elaborately jointed plates were provided for the feet, hands, knees, shoulders, and elbows—the last often much enlarged—to allow freedom of movement. The head was completely enclosed in a helmet with movable face-piece, rigidly attached to the neck-plate (gorget). The head and upper body of horses were similarly protected. In the sixteenth century lavish decorative work embellished the most splendid suits, rendering them quite unpractical in the field or even for fighting in the lists—a sport in which Renaissance monarchs still indulged. By its later decades the complete armour was no longer worn for actual fighting, though the thighs, arms, torso, and head were still protected. The weight required for reasonable protection was already becoming physically unbearable: armour made for the Duc de Guise in 1588, for example, weighs over a hundred pounds, without the leg-pieces. By the mid-seventeenth century infantry commonly wore nothing more formidable than a leather jerkin, and cavalry only an iron cuirass. A round open helmet was still usual.

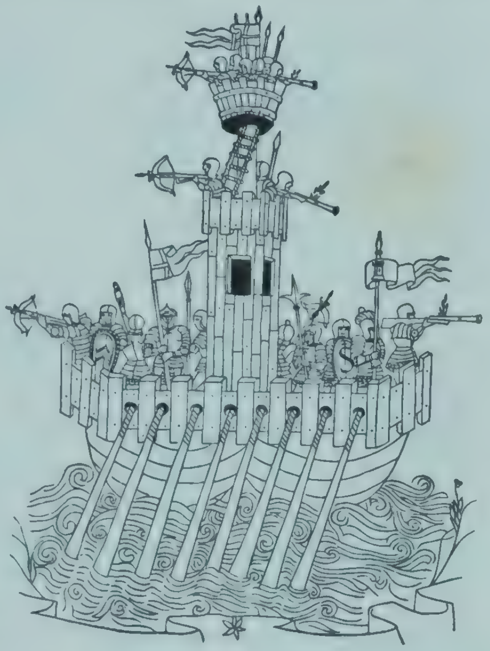

FIGURE 226—*Soldiers aboard a fighting-galley: from a woodcut of 1472. They include pikemen, crossbowmen, and hand-gunners. Note that the gun-stock rests on the shoulder.*

Since steel was not available in sufficient quantity, armour was worked with the hammer from wrought iron, chiefly on a flat anvil, though a round-topped anvil must have been used for some purposes. Figures 224 and 225 show the equipment of sixteenth-century armourers' shops. The sheet iron was worked cold; this was believed to give it greater strength. Rigid joints were made by rivets, moving-pieces turned on pins, and leather straps were used to fasten the various plates together.

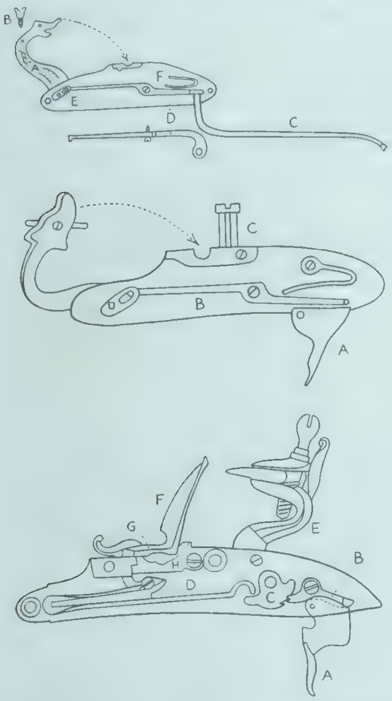

FIGURE 227—*Gun-locks (diagrammatic).* (Above) *Simple match-lock: the match is held in the jaws of the serpentine tightened by the screw* (B). *On squeezing the trigger* (C) *towards the stock, the sear* (D) *brings the serpentine down by the link* (E) *so that the match fires the priming in the pan. The sear and serpentine are forced back by the spring* (F); (Centre) *trigger match-lock: the trigger* (A), *acting upon a projection from the sear* (B), *forces down the serpentine.* C *is a shield to protect the eye from the flash of the priming* (*pan-cover omitted*); (below) *flint-lock; on pressing the trigger* (A), *the sear* (B) *is released from the tumbler* (C), *which rotates under the action of the spring* (D). *On the same shaft as the tumbler is the cock* (E) *carrying the flint, which strikes the steel* (F), *raising the pan-cover* (G) *attached to it. The sparks fall in the pan* (H).

III. HAND-FIREARMS

A variety of different terms—(h)arquebus, caliver (calibre), match-lock, fire-lock, musket, and so forth—are or were applied to the hand-guns of the sixteenth and seventeenth centuries. Technologically it is preferable to ignore the elaborate varieties represented in the larger modern armouries, in order to concentrate upon essential points of difference. A hand-firearm has three parts: a barrel to direct the shot and confine the propulsive force of the charge; a lock, controlled by a trigger, to fire the charge; and a stock to accommodate the weapon comfortably and firmly to the body. Each of these parts underwent considerable modification towards improvement in function. Considering the stock first, the modern type of shoulder-stock appears already in the early seventeenth century, but the modern form of pistol-grip is quite recent. Both have evolved from a straight piece of timber, to which a short barrel was crudely fastened (figure 226). It was clearly impossible to take a careful aim with such a weapon, and indeed the form of modern guns is closely associated with the development of the sporting-piece, for with the growing popularity of shooting as a recreation from the sixteenth century onwards the comfort of the sportsman and his desire to take an accurate sight at his game provided new incentives to the gunsmith. In war, where troops were massed in close formation and ranges were very short, accuracy was of small significance. The developed stock was carved from wood by the carpenter's traditional methods; in fine weapons it was ornamented with inlays and decoration in precious metal or ivory. Stock-making was a distinct trade, subserving that of the gunsmiths who made the metal parts and supplied the market.

While the performance of the gun depended upon the quality of the barrel, its reliability was determined by the lock, and this, the most delicate mechanism of the piece, was also that which was most developed. With negligible exceptions all early hand-guns were muzzle-loaded, and the charge of powder could be set off only by the direct application of fire. Unstable compounds, exploding violently on percussion, such as fulminating gold,[1] were known as chemical curiosities from the early seventeenth century, but they were too dangerous for practical use as detonators. Hence it was necessary to drill a small touch-hole into the barrel near the permanently closed breech through which fire could be applied from without, and to ensure reliability by placing a little fine priming-powder on the firing-pan with which the touch-hole communicated. In the earliest hand-guns, as with cannon, the priming was touched off by a slow-match held in the hand.[2] In the match-lock the action was mechanized, the match being held by an arm which brought its glowing end smartly down on the priming when pulling the trigger released a spring (figure 227).

The two-handed action and open pan of the primitive hand-gun were doubly inconvenient to the horseman, hence the first step towards a fully mechanical lock is found in the single-handed, wheel-lock horse-pistol, often a weapon of fair size. In the wheel-lock (plate 17), probably an Italian invention of about 1520, a spring is placed under tension by applying a key to a squared shaft; on pressing the trigger the spring is released, causing a wheel with a serrated edge to revolve against a piece of pyrites. The sparks so produced ignite the priming. The wheel-lock, though reasonably efficient when in good order and kept dry, had two disadvantages; time was required to fit the key and wind up the spring, and the mechanism could not be operated a second time, after a misfire, until this was done. It was also somewhat delicate. For the infantryman's musket the match-lock was preferred until a little after the mid-seventeenth century, despite

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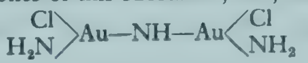
[1] There are two or three varieties of this substance; one, according to Raschig, is $HN{:}Au.NH_2,\frac{3}{2}H_2O$, and another, according to Weitz, is  $\begin{matrix}Cl\\H_2N\end{matrix}\!\!>\!Au{-}NH{-}Au\!<\!\!\begin{matrix}Cl\\NH_2\end{matrix}$ with some of the chlorine replaced by $-OH$, hydroxyl.

[2] Slow-match was a kind of coarse twine heavily impregnated with saltpetre so that its lighted end maintained a steady glow. It was not uncommon for troops to keep a tobacco-pipe alight to ignite their matches when required.

the difficulty of keeping the match alight in bad weather. The next important step was the invention of the flint-lock; the flint was held in a screw-clamp, at the end of a pivoted arm, which was cocked by pulling it back against a strong spring (figure 227). On pulling the trigger the arm was released and a sharp edge of the flint struck a roughened plate just above the firing-pan so that sparks flew into the priming.

The flint-lock was far from being a perfect device. Its action was still affected by damp, though less so than that of earlier locks, and it was subject to misfires. But it could quickly be cocked and discharged a second time, and the mechanism was strong and simple enough to resist hard usage. It remained as the standard lock on all hand-firearms until the early nineteenth century, when an efficient percussion-cap was introduced. Incidentally, the 'knapping' of gun-flints (which still survives, for supplying the African market, at Brandon in Norfolk) was the last relic of the old art of shaping flint implements (vol I, figures 57, 58).

Whatever their type, all gun-locks are evolutionary descendants of the cross-bow lock (vol II, figure 656). Etymologically the word is identical with 'lock' as applied to a door-fastening, and the similarities between the two mechanisms are sufficiently obvious, in the frame-plate or -plates, the long U-springs, fixing-pins, and system of levers. Gun-locks were made by the same methods, and with the same tools, as were ordinary locks, and probably originally by the same craftsmen, from whom the gunsmith learnt this part of his skill. In sixteenth-century fire-arms the lock was often set upon the right side of the stock, not inset in a mortice as was the later practice. It was frequently chased and otherwise decoratively treated.

The excellence of a gun is determined by the workmanship of its barrel, which must be perfectly straight and smooth (or uniformly rifled), and of constant internal diameter. The metal must be sufficiently tough to withstand the explosion of the charge without cracking or stretching, even when hot, and rigid enough to resist accidental damage. At short ranges the impact of the projectile at a given velocity will be roughly as the cube of the bore, the charge increasing in the same proportion as the projectile's weight; hence, as muzzle-velocities were low, early military weapons tended to have large bores and weighty projectiles. For sporting purposes a lesser calibre was, and still is, usually adequate. The accuracy and muzzle-velocity of the weapon are to some extent proportional to the length of the barrel; for which reasons some mid-seventeenth century match-locks were made with such massive barrels that the gun could not be managed without the aid of a rest to support some of its weight (plate 17).

For ease in manufacture spherical lead shot was invariably used, cast in a linked two-piece bullet-mould. Since considerable variations in size and shape resulted, it was impossible to hope for an accurate fit inside the barrel, and in any case the ballistic characteristics of a spherical projectile are poor. It was normal to allow a considerable 'windage', so that the shot was loose in the barrel; a wad of paper or other soft material was rammed down on the powder before the ball was inserted, to keep the powder in place. The wad also, by preventing an easy escape of the gases produced, ensured a sharp explosion and a maximum effect on the projectile. A second wad could be used to retain the ball, but it was not uncommon for it to roll out of the barrel before the gun was discharged.

All medieval hand-guns, and the great majority of fire-arms before the nineteenth century, were made smooth-bore owing to the difficulty of cutting rifling, though the ballistic advantages of the rifled barrel were recognized. Various methods of forming the barrel were adopted, all of which, in the days before drawn tubes, involved the welding of seams. Each began with a strip or strips of iron, sometimes forged from old nails. The simplest method was to take a strip, somewhat longer than the barrel was intended to be, bend it longitudinally upon a cylinder into a tube with the edges slightly overlapping, and then weld the edges together (figure 228). The tube might then be twisted so that the joint ran spirally round the barrel. Another was to roll short strips into tubes, with welded joints, and weld these end to end to make a barrel of the required length; in this way the thickness of the metal could be decreased from the breech to the muzzle. A third way, adopted in the eighteenth century, was to form a thin tube by the first method, and upon this to wind a long strip of iron somewhat less than an inch broad and about 0·2 in thick, reduced on each edge, overlapping the turns slightly. The whole was then welded together and bored out so that very little of the inner tube remained. Barrels made in this way were stronger, since the welded joints were transverse rather than longitudinal. In all cases the barrel was bored or reamed out by means of a revolving cutter mounted on the end of a long shaft which was gradually advanced into the barrel; in the eighteenth century, if not before, the boring-machinery was driven by water-

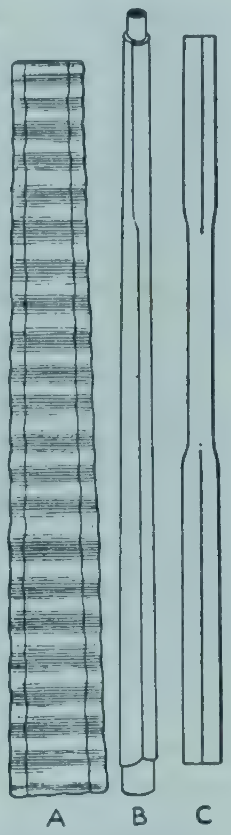


FIGURE 228—*Steps in forging a gun-barrel.* (A) *The iron strip;* (B) *the strip rolled on a rod into a tube;* (C) *partially forged barrel.*

power (figure 229). The exterior of the barrel was ground smooth on another machine. Pistol-barrels of brass or bronze were cast hollow before boring. The public 'proof' or testing of gun-barrels before they were sold was commonly required from the early seventeenth century onwards.

The inventor of the rifled barrel is unknown, but examples said to date from soon after 1525 exist (plate 17). The combination of the rifled barrel with the wheel-lock made an accurate and convenient sporting-gun possible, though the expense of such a weapon restricted its use to wealthy amateurs of shooting. This was just becoming popular as a sport: 'so great was the delight I took in shooting', wrote Cellini about 1520, 'that it often diverted me from the business of my shop.' He was a good marksman, bringing down pigeons with ball-shot (sitting birds, however, for the art of shooting on the wing was not yet practised), and his fowling-piece carried two hundred paces point-blank [2]. This was probably not a 'screwed gun' or rifle. The invention of rifling has been attributed to a gunsmith of Nuremberg named Kotter or Kutter, about 1520: this seems to be a mistake since rifles signed by Kotter and dated 1616 are known in Paris. The first use of the rifle for military purposes appears to have been in Germany, where the Landgrave William of Hesse in 1631, and the Elector Maximilian of Bavaria ten years later, armed troops of light horse with rifled carbines.

The usual method of loading a rifle, then and long after, was to make the ball a little larger than the bore within which the rifles had been cut, and hammer it down upon the powder with the aid of a stiff ramrod. (Early Rifle Corps men were equipped with light hammers for this purpose). The lead ball expanded into the rifles, so fitting them exactly. The alternative breech-loading method was well known and even applied to cannon; the difficulty was to apply it with safety. Three sporting-guns made for Henry VIII were loaded with steel cartridges, inserted in the breech, which was closed by a hinged block. A touch-hole in the breech, aligned with another in the cartridge, allowed the charge to be fired.

Unusual weapons of this kind, though they reveal the measure of the gunsmith's skill, were never suitable for production in quantity. Inventors were constantly active, throughout this period, in attempting to render practicable ideas beyond the technological equipment of their time. Thus Pepys was present when 'a gun to discharge seven times, the best of all devices that ever I saw, and very serviceable' was shown to the officers of the Ordnance. If, as he says, there were 'many thereof made', they certainly were never widely used. The attention of the Royal Society was drawn, two years later, to a 'rare mechanician' who claimed 'to make a pistol shooting as fast as it could be presented, and yet to be stopped at pleasure; and wherein the motion of the fire and bullet within was made to charge the piece with powder and bullet, to prime it, and to bend the cock'. Such an 'automatic', if it ever existed, could have been no less of a

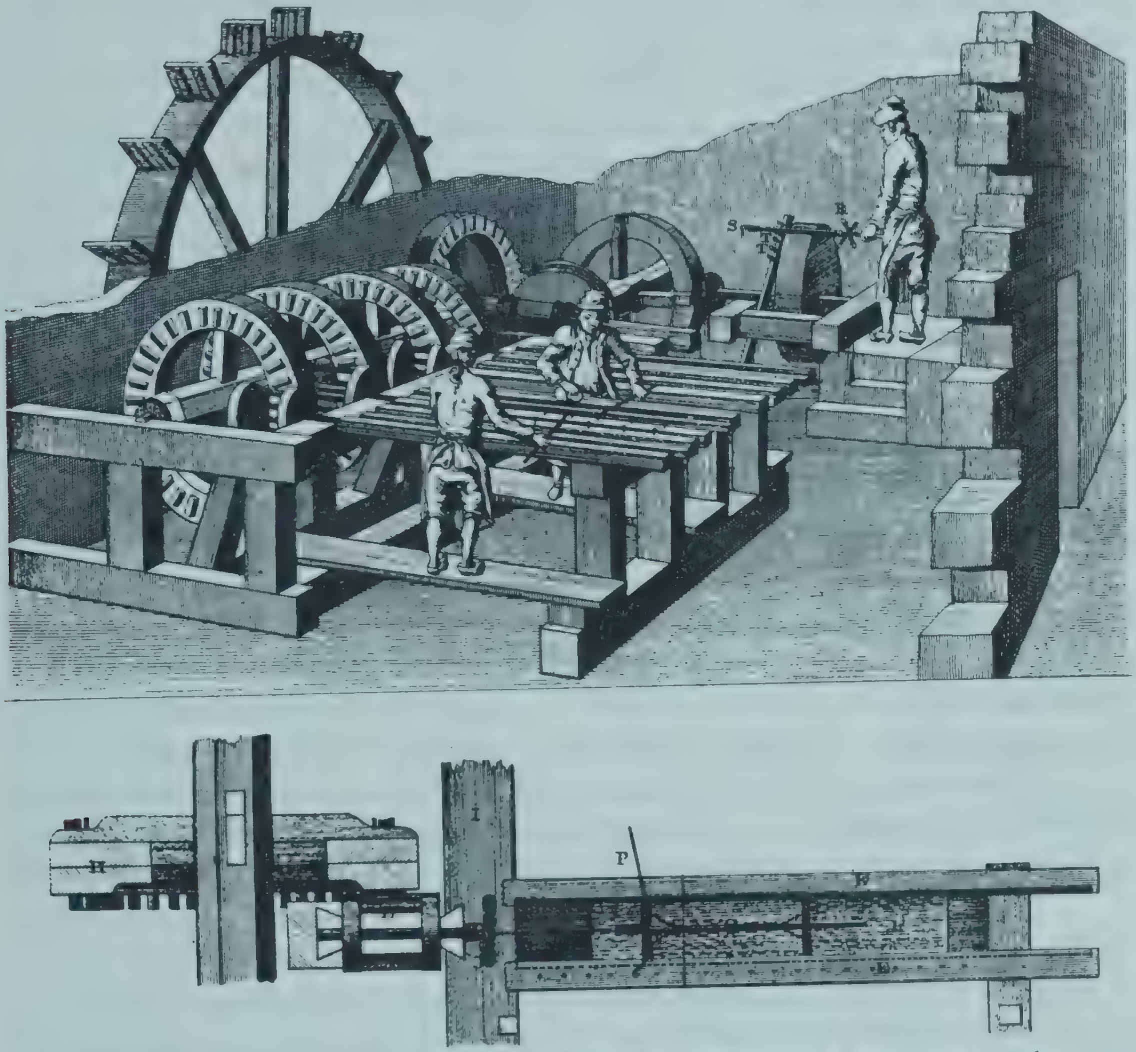


FIGURE 229—(Above) *Machinery for boring gun-barrels, with the outside of a barrel being ground on a stone at the rear;* (below) *plan view of one boring-bench. The rectangular boring-bit of tempered steel,* 10 *in long, is welded to an iron rod* $3\frac{1}{2}$ *ft long* (N) *rotated by water-power through the wooden gearing. Upon the bench* (E) *slides a carriage holding the barrel, which is forced on the bit by a lever* (P) *acting upon the fixed pins. Twenty-two bits, successively larger, are used to enlarge the bore of the barrel from* $\frac{5}{12}$ *in to* $\frac{7}{12}$ *in. The trough* (F) *holds water for cooling.*

curiosity than the air-guns with which the philosophers also experimented, and no more useful for military purposes [3].

From the feebleness of the explosive used, the loose fit of the spherical projectile, and the crude methods of making the barrel the military hand-firearms of the seventeenth and eighteenth centuries had poor ballistic characteristics.

Even their locks frequently failed to work properly. Their muzzle-velocity was low, hence the extreme range was short and the point-blank trajectory hardly greater than that of a cross-bow—250 yds would be an optimistic estimate of their effective range, and the useful range was no more than half this. These defects were not of great importance, however, in the prevailing state of warfare when armies engaged closely in dense formations. Marksmanship was little practised until small corps of riflemen were raised towards the end of the eighteenth century. The fine rifled sporting-gun was a far superior weapon, and it was from their private customers, rather than from their mass supply to government departments, that gunsmiths received the incentive towards technical improvements.

There was no scientific study of the interior and exterior ballistics of small-arms until towards the middle of the nineteenth century, though experiments on musket-shot were made by Benjamin Robins ('New Principles of Gunnery', London, 1742). Many misapprehensions, leading to errors in design, persisted until a century ago. For example, it is stated in Diderot's *Encyclopédie* (1751–72) that the benefit obtained from a rifled barrel is due to the tight fitting of the ball, which prevents it flying out easily so that the powder-gases build up compression and act on it with greater force. Yet Robins had correctly pointed out that the function of rifling was to cause the ball to spin, so that it maintained a uniform direction in flight and resisted tendencies to swerve set up by air-resistance. As a result of the common error represented in the *Encyclopédie* rifles were sometimes made with almost useless straight grooves, or with so little twist that the projectile was given an insufficient rotation.

IV. CANNON

Here again it is unnecessary to enter into details regarding the multiplicity of types, sizes, and names prevailing at this period. At the beginning cannon, like small-arms, were known by largely fanciful names, such as serpentine, bastard, culverin, saker, falcon, and the same name was applied to guns of widely ranging weights and calibres. By the end of the seventeenth century the number of types was reduced, and they were known simply by the weight of the projectile (table I). Standardization proceeded rapidly in the seventeenth century, and did much to ease the administrative burdens imposed on commanders in the field, as well as simplifying the task of training efficient gunners. In the earliest history of artillery those who cast cannon had also served them in battle and probably supplied the powder and shot too, and even in the sixteenth century the expert gunner was supposed to know a great deal about the manufacture and

TABLE I

French Ordnance 'of the latest type' in 1697

From Surirey de Saint-Rémy, *Mémoires d'Artillerie*, Paris, 1697

Type	*Weight*	*Length*	*Range at 45°*
24-pounder	3000 lb	6·65 ft	4500 yds
16-pr	2200 lb	6·20 ft	4040 yds
12-pr	2000 lb	6·10 ft	3740 yds
8-pr	1000 lb	4·99 ft	3320 yds
4-pr	600 lb	4·75 ft	3040 yds

The ranges may be regarded as very uncertain. Windages allowed vary from 0·21 inches in the largest guns to 0·11 inches in the smallest.

testing of guns, compositions of gunpowder, and so forth. By 1700 such extensive skill was no longer requisite. The founding of cannon and the manufacture of ammunition were conducted in highly developed establishments, sometimes (as in France) state-owned, and the field-gunner had only to learn the proper handling of standard equipment.

The experimental period in heavy artillery ended before the close of the sixteenth century, from which time the muzzle-loading, smooth-bore, cast-metal gun was that universally employed in all sizes and for all types of service. Iron, bronze, and brass were all cast to make artillery. Iron was the cheapest metal, and would withstand the roughest service, but it was more subject to corrosion than the cupreous alloys, and more liable to dangerous fractures. Hence bronze guns, though more readily worn by iron shot, were generally regarded as superior.

In the age of experiment many strange cannon were produced. In the early fifteenth century, as already mentioned (vol II, p 727), the built-up iron gun or 'bombard' was common for siege-work. Some of these, such as 'Mons Meg' at Edinburgh, were made in two parts, a chamber (of smaller bore than the barrel), containing the powder, being screwed into the breech of the gun. One of the most massive of early cast bronze guns, made by the Turks for the siege of Constantinople in 1453, shows the same principle. Other breech-loaders have the barrel firmly anchored to a wooden frame ending in an upright member: the separate chamber fitted into the breech and was held firm by a wedge placed between it and the upright member of the frame. Small cannon, such as wall-pieces, were made to load at the breech until the sixteenth century was well advanced; in these the iron chamber was wedged into the stirrup extending backwards from the breech. Effective use of breech-loading was, however, utterly impracticable in the existing state of gun-making and metal-working, for not only was there always extreme danger of the chamber being blown from the gun, but the leakage of explosion-gases was so great that the force of the projectile was very much reduced. For naval use admittedly the breech-loader had the great advantage that the gun did not have to be run inboard for loading; this ceased to be of great significance when the size of ships increased, and the bore of guns was enlarged in proportion to their length.

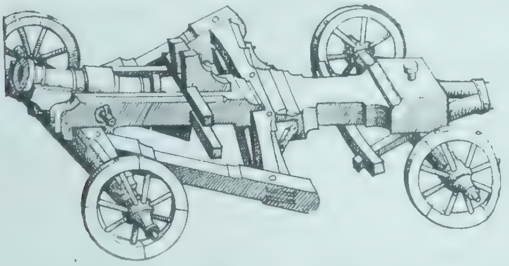


FIGURE 230—*Late fifteenth-century gun-carriage; the cannon is mounted on stout timber, and can be traversed by moving the breech end within the framework of the carriage. Note the pivoted front axle.*

Early illustrations indicate that there was also much experiment in the mounting of guns. At first, relatively small barrels were solidly held to large baulks of timber laid on the ground or supported at a suitable angle, the recoil being limited as far as possible. In an improved form of this mounting the barrel was made to pivot roughly at its point of balance and the breech end was movable upon a quadrant, so that the angle of elevation could be easily adjusted. Such cannon were transported by loading them into carts. The next step was the construction of a cumbersome wooden gun-carriage upon which the barrel was permanently mounted (figure 230), a development following from the fitting of four wheels to the baulk to which the gun had been fastened. Towards the end of the fifteenth century, trunnions were cast upon the gun-barrel, upon which it could pivot for adjustment in elevation, and the field-carriage with its trail and transom assumed a form essentially similar to that still used (tailpiece). The transom joins the two cheek-pieces of the carriage, under which the axle is slung, and which extends to form the trail supporting the gun in the firing position. The trunnions rest upon the cheeks and are held down by iron straps. The gun is laid by inserting wedges between the breech and a cross-piece of the trail. Early gun-carriages and their wheels were of wood, strongly reinforced with iron; they were rather narrow, with wheels disproportionately large.

Among other experimental artillery there were guns having more than one barrel, cast singly or together, and man-killing weapons consisting of a number of small barrels fired simultaneously by a train of powder mounted on a mobile framework. The device was even attempted of mounting a number of barrels radially on a turn-table, to be loaded and fired in rapid succession.[1] None of these inventions achieved permanent success, since all were displaced by the simple cast-metal gun mounted on a suitable carriage.

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[1] Hand-guns of the pistol type, with revolving chambers firing through a single barrel, were known in the sixteenth century.

Naval ordnance was precisely similar to that used on land, though commonly shorter in the barrel and very powerful on the lower decks of great ships. The gun was mounted on wooden trucks running on four rather small wheels. Ropes from the truck to the wall of the ship limited the inboard recoil. Naval guns also were laid with a wedge inserted between the breech and the framework of the truck.

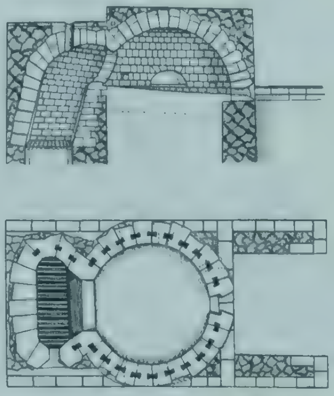

FIGURE 231—*Section and plan of furnace for melting bronze for gun-founding. 1603.*

Large cannon, presumably of cupreous metal, were already being cast soon after the mid-fourteenth century, but a great development in the art of handling masses of molten metal took place in the fifteenth and sixteenth centuries, particularly with the development of the blast-furnace to make iron-casting possible. The surviving evidence indicates that fundamentally the same methods were employed from the beginning until about 1750. Thus an account of the casting of the great cannon used against Constantinople in 1453 could easily be applied to the operations of European foundries in the seventeenth century:

> [The founders] take a quantity of very fat clay, the purest and lightest possible, which they make plastic by kneading it for several days. The mass is knit together and prevented from breaking by the addition of linen, hemp and other fibres. The whole is worked into a tough and compact mass. Then they make a long cylinder to serve as the core of the mould. Another [hollow cylinder] to receive the first is made, but larger in order to leave a void space between the two: it is the space intended to receive the bronze pouring into it from the furnace to take the form of a cannon. The exterior [of the mould] is made of the same kind of clay, but entirely surrounded and reinforced by iron, timber, earth and stones built up around it to prevent the immense weight of bronze from fracturing it and spoiling the cannon. Then they erected two furnaces, one on either side and close to [the mould]. These towers were made very strong and fortified internally with brick and a very fat well-worked clay, and on the outside built with large cut stones and cement. And they cast into the furnaces a mass of copper and tin [weighing] about 1500 talents [37 tons]. On it they threw charcoal and wood, arranging that the metal was covered below, above and on all sides. Round about were the bellows, working without intermission for three days and nights until the whole of the bronze, melted and liquefied, became like water. Then the outlets being tapped the bronze flowed through earthen pipes into the mould until it was filled and the interior cylinder covered so that the metal lay 30 inches deep upon it [4].

Biringuccio (1480–1539), who describes methods of casting in bronze in the sixth chapter of his *Pirotechnia* (1540), gives a full account of the manufacture of cannon. This was one of the more difficult applications of the founder's art, though the essential principles were already employed in bell-founding as described by Theophilus in the Middle Ages (vol II, p 64). For cannon the

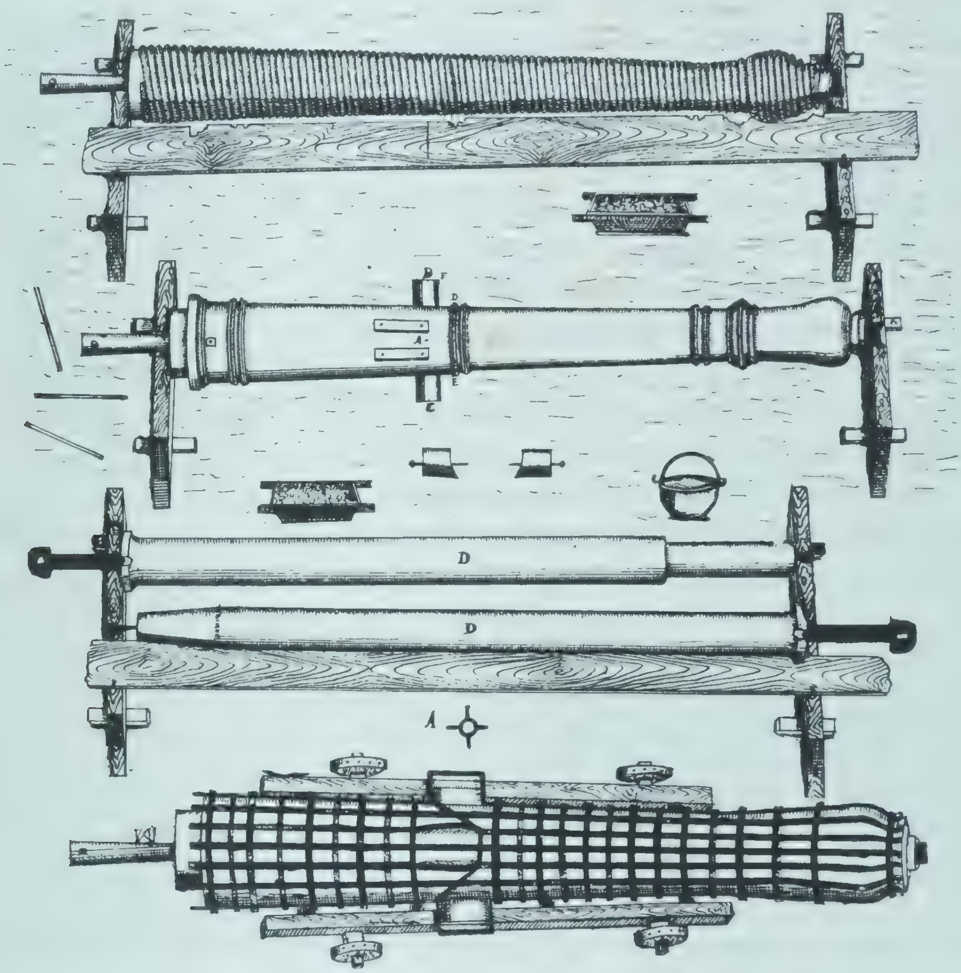

FIGURE 232—*Making moulds for cannon.* (Top to bottom) *Two stages in the preparation of the 'model'; the mould-core; the complete mould, bound with iron, ready to be filled. 1603.*

same furnaces, moulding-clay, and methods of casting were used as for all work in bronze (figure 231), but Biringuccio issues a special warning that cannon-moulds must be filled slowly; the proportion of tin to copper in the bronze was about 1:10, with variations, for the masters used their discretion according to judgement and experience [5]. Nor were there any firm principles of design: 'In every age', writes Biringuccio, 'men have proceeded to make and still today make [cannon] as they think it will be best to use them for their purpose or according to the wishes of whoever has them made or of the masters who make them' [6].

Normally the founder began by making with clay laid on a wooden spindle, or by turning a larger piece of timber on the lathe, an exact model of the exterior of the cannon to be cast, attaching the various prominent pieces of decoration and the trunnions with light pins. This model extended to the breech end of the gun, but the breech itself was made separately. This model was well dried, and covered with a mixture of ashes and fat to prevent adhesion of the thick layer of clay, forming the actual mould, next spread over it. Fine slip was carefully applied first, then coarser clay with dung and straw added to make it porous as the mould was gradually increased in thickness. When the work was nearly finished iron wires were incorporated in the clay coating to give greater strength, and finally the mould was bound by a reinforcement of iron bars (figure 232).

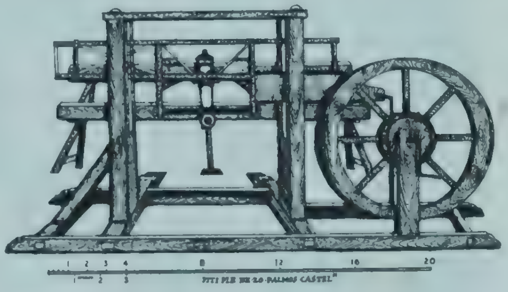

FIGURE 233—*Machine-saw for cutting off the 'gun-head'. 1603.*

When the mould was dry, the spindle within was knocked out, the trunnions and other prominent pieces were removed, and the model was withdrawn from the mould altogether. The mould for the breech was made separately; Biringuccio says that it should be ornamented with some piece of sculpture to make the gun beautiful. This mould was made with a shoulder to fit into a recess cut in the main mould for the barrel; when dry, it was placed in position and fastened to the iron bars enclosing the main mould. The third piece of the mould was the core, formed from clay on an iron bar, which was commonly cylindrical but might be shaped to give a special form to the chamber where the powder would be. The core was held in place by an iron chaplet inserted at the breech-end of the main mould, and by a clay disk or a second chaplet at the mouth of the mould, which was enlarged to form the 'gun-head'. The weight of metal in the gun-head, when the mould was filled, pressed the bronze below it into the recesses of the mould and prevented the occurrence of bubbles in the casting.

With the three pieces of the mould firmly assembled it was thoroughly baked, lowered into a pit near the mouth of the furnace, and filled with molten metal. When cool, the mould was broken up to extract the gun, the gun-head cut off with a saw or chisels, and the exterior neatly finished with hammer, chisel, and file (figures 233, 234). The cannon was now ready to be bored, to have the touch-hole drilled, and to be mounted and proved (figures 235, 236). A good gunner would certainly satisfy himself that the core had been properly placed by the founder, so that the bore was truly concentric with the exterior of the gun; otherwise it would never shoot well.

There is no full description of the methods of making the moulds for iron guns and casting them, but as the techniques of the bronze-founders were certainly imitated by the iron-founders, one may assume that there was little difference in practice. Iron guns, however, were not lavishly ornamented as were those of bronze.

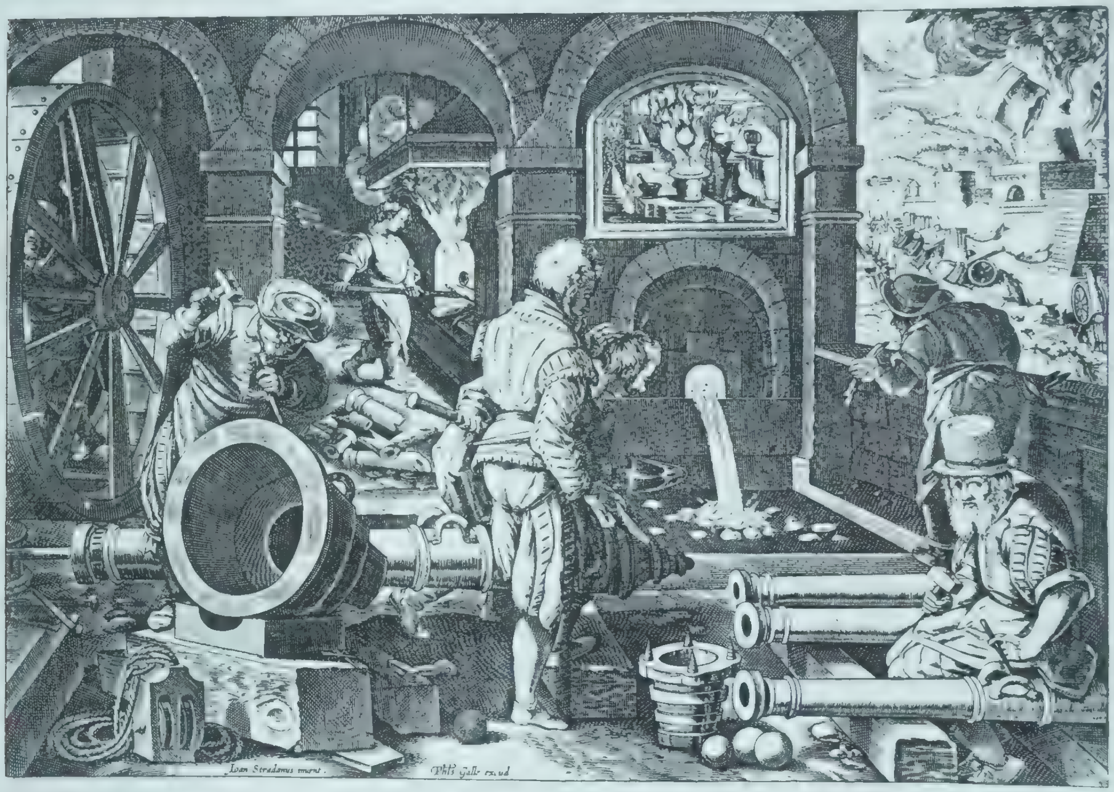

FIGURE 234—*Sixteenth-century bronze-cannon foundry with the furnace, which is being tapped, in the background.* (Left) *A treadmill provides power for the horizontal boring-bench;* (centre and right) *finishing a mortar and a cannon with the chisel. The vignettes show the mythical invention of gunpowder by 'Berthold Schwarz', and an attack upon a fortified place.*

The results of this method of manufacture are obvious. First, since a new mould must be made for each gun, no two could be identical in dimensions and behaviour, and the reduplication of labour was greatly increased. Secondly, as the metal was cast and subjected to no further treatment, it was relatively weak, so that the weight had to be increased to give sufficient strength. Iron guns were commonly cast straight from the smelting-furnace; thus the metal was impure, highly carbonized, and brittle. Prince Rupert in England, about 1678, invented a method of 'annealing' iron ordnance in glass-works, which may have rendered the metal less liable to fracture, but it was not adopted, possibly on grounds of expense [7]. Thirdly, the piece was not accurately bored but reamed out, so that it might be, and often was, extremely erratic. The gunner had to know the idiosyncrasies of his piece at all ranges before he could undertake to lay it with some assurance of hitting the mark.

Since the sixteenth century, and probably earlier, guns had been bored by water-power. Biringuccio (1540) implies that boring was a fairly recent innovation: 'for greater caution, for the beauty and safety of the gun, and to make sure that it achieves its purpose of shooting with perfect accuracy, soldiers and master gunners began to desire that both large and small [cannon] should be bored, as they do arquebuses and iron muskets' [8]. He illustrates a crude horizontal borer, worked by hand- or water-power, with various cutters. The gun is drawn forward against the cutter by a windlass. The vertical borer, however, must have been known not many years later, for it is described in Spain in 1603. An almost exactly similar machine is depicted in Diderot's *Encyclopédie* (1751–72). The bit was mounted upon the end of a long shaft, supported only at its lower extremity, so that it was incapable of cutting a true cylinder or correcting a misalignment of the core made in casting the gun. The practice of boring out a solid cast gun is said to have begun in 1713, but in 1747, when the Dutch authorities abandoned hollow-casting in favour of the new method, they took such careful precautions to preserve the secrecy of their technique and machines that it would seem that hollow-casting was still in general use elsewhere. It was continued in the royal gun-foundry at Woolwich until after 1770. About this time, the English iron-master, John Wilkinson (1729–1808), developed an improved machine for boring

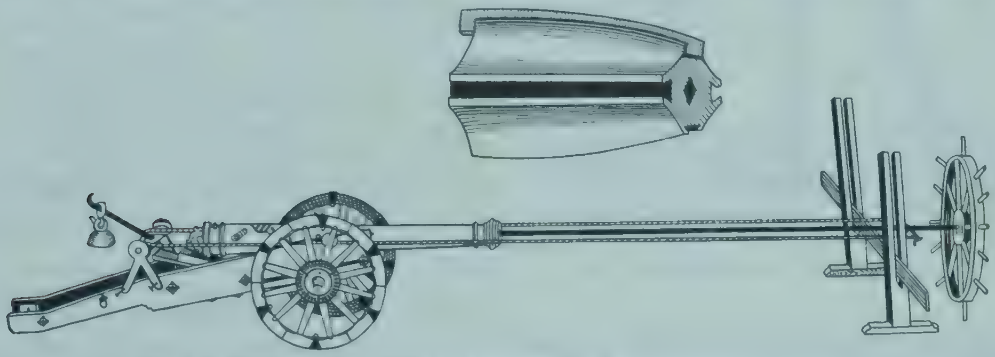

FIGURE 235—*Simple horizontal borer operated by a capstan. The weight acting on the windlass attached to the gun-carriage presses the cannon forward upon the cutter.* (Inset) *Bronze boring-head, with one steel cutting-blade in place. 1603. In vertical boring-machines the cannon was pressed by gravity upon the cutter, which was turned by animal- or water-power.*

cannon, which was also used to cut more accurate cylinders for Boulton and Watt's steam-engines.

Whether cannon were directed against troops, ships, or fortifications they were normally aimed point-blank, or at elevations little above the horizontal. For certain purposes, however, it was desirable to use a high trajectory, with an elevation of 45° or more, in order to bombard the interior of a fortified town, or targets hidden behind a hill or other obstruction. It was realized that greater destructive effect could be obtained if the projectile was not solid, like round-shot, but contained a charge of powder exploded by a fuse. These objects were combined in the mortar and mortar-bomb, the former being probably coeval with cannon, and the explosive bomb an invention of the late fifteenth century.[1] The mortar had a short and wide bore, with a powder-chamber of much smaller diameter which was sometimes detachable. The bomb was hollow-cast, with a touch-hole or plug into which the slow-match was inserted. The earlier practice was for the bombardier, after he had loaded and set his mortar to his satisfaction, to take a linstock in each hand and with one light the fuse in the bomb, immediately afterwards touching off the mortar with the other. The danger was that if for some reason the mortar misfired the bomb would probably burst inside it. In the seventeenth century a safer method was adopted, whereby the bomb was fitted with readily inflammable material at the touch-hole capable of firing a fuse leading through a tube to its charge. It was placed unlighted with the touch-hole next to the propellant explosive in the mortar so that when the latter ignited the flame passed to the combustible on the bomb and so to the fuse.

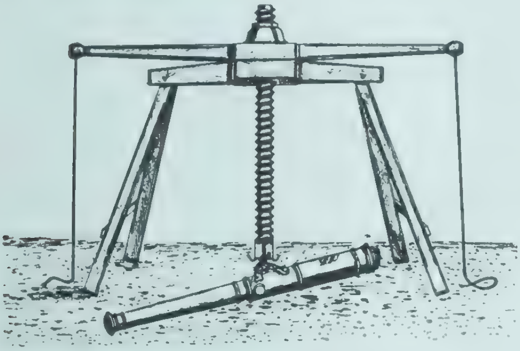

FIGURE 236—*Screw-jack for raising cannon. 1603.*

Mortars were made by the same methods as cannon, first built-up of wrought iron, and later cast in iron or in cupreous metal (figure 234). Later practice was usually to mount them in trunnions, attached low down near the chamber, in a strong wooden frame, without wheels, upon a firm platform. Elevation was given by wedges inserted below the mouth of the piece. Mortars were also mounted in small bomb-vessels in the second half of the seventeenth century, for bombarding port-installations and defence-works from the sea.

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[1] According to Biringuccio mortars were 'not esteemed by us moderns': they returned to favour about the middle of the seventeenth century.

During the same period armies adopted a small fused bomb, or grenade, thrown by hand. Corps of grenadiers were first raised about 1670.

TABLE II

Characteristics of French Mortars, 1697

From Surirey de Saint-Rémy, *Mémoires d'Artillerie.*

Calibre	*Charge*	*Elevation*	*Range*	*Change of range per degree of elevation*
8 in	½ lb	5–45°	210–1890 ft	about 42 ft
,,	¾ lb	31–45°	1922–2790 ft	,, 62 ft
,,	1 lb	34–45°	2870–3690 ft	,, 82 ft
12 in	2 lb	5–45°	240–2160 ft	,, 48 ft
,,	2½ lb	36–45°	2160–2700 ft	,, 60 ft
,,	3 lb	37–45°	2664–3240 ft	,, 72 ft

The characteristics of the high trajectories, 45°–85°, would correspond approximately to those of the low trajectories, 45°–5°.

V. FORTIFICATION

Profound changes in the art of static defence were an inevitable consequence of the introduction of gunpowder and firearms into warfare. Vertical walls and towers, however thick, were vulnerable to shot and mining, and the more massive and complicated defences of the developed late medieval type were, the greater was their tendency to restrict the active operations of the besieged, and even shelter the attackers from missiles and sallies. Sieges raged around fortifications of the old type until the sixteenth century was well advanced, however (figure 234), and even in the English Civil Wars (1642–50) a stoutly defended medieval castle, like Corfe, in a position of peculiar natural strength, could resist small forces for a considerable period. Thus the usefulness of the medieval castle might have diminished less rapidly had it not been that, with larger forces engaged, they could no longer contain a significant fraction of them. A castle holding a few score men could be safely neglected, or neutralized by a small detachment until it could be reduced at leisure, without affecting the main campaign. An effective defence work must be capable of holding some thousands of men and much artillery, stores, and equipment; it requires roads or rivers for supply. For these reasons, as well as the desire to afford protection to the civil population, fortified towns rather than castles became the pivots of the new defensive systems. Of course, many medieval towns had been strongly fortified, as was Carcassonne in the thirteenth century (figure 191).

To guard the perimeter of a town, works less costly than those of medieval castles were desirable. Their function changed, too. The walls and towers of a castle were built to resist entry by battery or scaling: the walls and ditches of a fortified town of the seventeenth century were less conspicuous, but they afforded good protection to troops. The defence relied mainly not on opposing static physical obstacles to the attack, as in the castle, but on its men and guns, to which ramparts and ditches were auxiliary. Thus one of the chief concerns of fortification-engineers was to secure the best possible combination of fields of fire for their own forces, while hampering the enemy's deployment of his guns and restricting their effect as far as possible.

This was achieved largely by adopting a regular geometric plan for the defence-works, which consisted mainly of trenches and low extended parapets. The new system of fortification was largely of Italian origin, the problem arousing the interest of some of the best minds of the age, among them those of Machiavelli (1469–1527) and Leonardo (1452–1519). The German artist Dürer also wrote a treatise on fortification (1527). The first step would seem to have been the use of a bulwark, made of earth supported by hurdles, for the protection of gates and extending before long walls, in order to establish gun-positions round the main defences. (The besiegers, too, are often shown sheltering their guns with the aid of gabions, round hurdle-work containers filled with earth.) Ordnance was also mounted on cut-down towers, and in embrasures cut in their bases, but not to great effect.

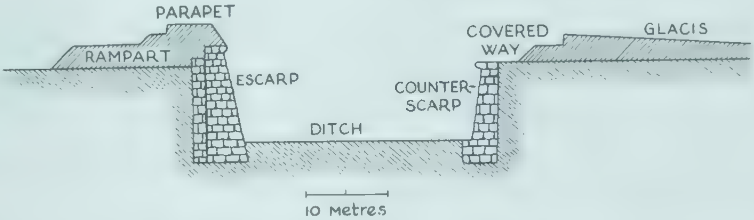

FIGURE 237—*Late seventeenth-century type of fortification, shown in section.*

An improvement was made by substituting for the bulwarks masonry-faced walls, heavily banked behind with earth to lend support and provide firing-platforms for artillery. To make the masonry face more resistant to artillery it was built with arches at the rear running back into the supporting-bank, or rampart. As the wall was lower, a ditch before it as an obstruction to assaulting-parties was a valuable precaution, more necessary than with the very lofty walls of the medieval castle, and the wall could be sunk to form one face of the ditch (the escarp). The outer side of the ditch was also lined with masonry (the counter-scarp) to make it more difficult to enter. Since the defending forces needed ground on which to form for a sally across the ditch, a covered way was built on the far side behind the glacis. Thus emerged the type of defence-work shown in section in figure 237. While every part of the defence from the glacis inwards was covered from shot coming from without, the whole of the work was open to fire from within should the besiegers enter any part of it.

The principal object to be attained in laying out the plan of such works on the ground in relation to topographical features and the development of the site was the provision of the maximum amount of flanking-fire and the opportunity to erect as many batteries and defence-posts as possible. This could best be achieved by interrupting the fairly smooth circular or polygonal perimeter of an ordinary town, that is, by building works projecting from the line of the main inner wall. At first, partly on account of the vast expense involved in completely reconstructing medieval defence-works, this was done by building bastions, fire from which could be directed parallel to the main walls, while the walls of the bastion were themselves enfiladed from the walls (figure 238). To defend long walls many bastions were required, and the area within the bastion had to be sufficient to hold numbers of troops and guns, so that its walls in turn had to be broken by angles to provide more adequate flanking-fire. The logic of this development led to the complete abandonment of the flat curtain-wall: instead, the site was surrounded by an interlacing system of regular or irregular polygonal defences, the angles made by the bounding-lines being calculated to give the highest concentration of cross-fire.

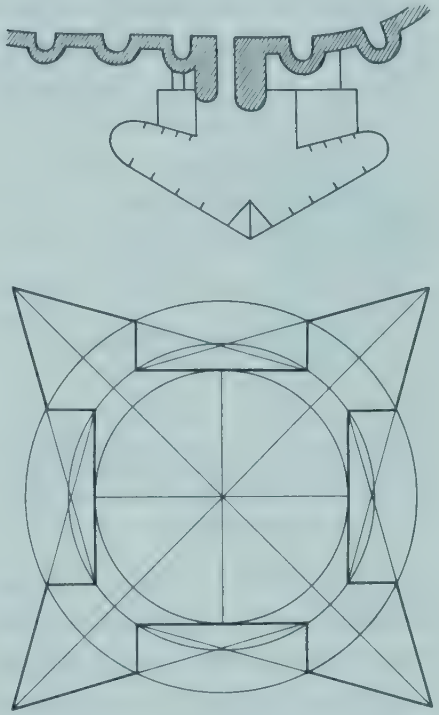

FIGURE 238—(Above) *Modern bastion adapted to a medieval wall: from Troyes;* (below) *trace of a simple polygonal fortification with four bastions making right angles with the curtain. 1696.*

The possible combinations of triangular elements to obtain the result sought were intensively studied from the end of the sixteenth century by applied mathematicians and engineers, of whom probably the most famous (as a scientist) was the Dutchman, Simon Stevin (1548–1620). The theoretical elements of fortification were commonly taught along with mathematics, and many supposedly impeccable systems, derived rather from familiarity with ruler and compasses than from actual experience of sieges, were propounded (figure 238). In fact the greatest exponents of the art of siege-warfare, offensive and defensive, in the second half of the seventeenth century, Vauban (1633–1707)[1] on the French side and Coehoorn (1634–1704) on the Dutch, did not mechanically apply a predetermined geometrical scheme to each situation, but varied their methods according to the possibilities and the existing works of the place in question. Both devoted much attention to artillery, as well as to earthworks, Vauban inventing the *tir à ricochet* and Coehoorn a form of mortar known by his name. It was only in the eighteenth century that the art of defending places and conducting sieges became for a time thoroughly stereotyped and reduced to rule.

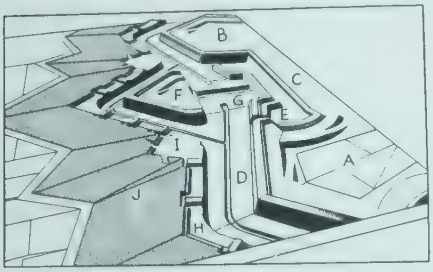

FIGURE 239—*Vauban's 'first system' of fortification.* (A, B) *Two forms of bastion;* (C) *curtain;* (D) *ditch;* (E) *tenaille;* (F) *demi-lune;* (G) *corridor;* (H) *covered way;* (I) *place d'armes;* (J) *glacis.*

The enormous public expenditure on defensive works, particularly in France, is well illustrated by the labours of Vauban. These gave a formal appearance to countless towns—in eastern France especially—which they still preserve, though modern suburbs have since grown up beyond the remains of Vauban's walls and ditches. His methods varied somewhat during his career, for he always maintained that 'the Art of Fortification does not consist in rules and systems, but solely in common sense and experience' [9]. His so-called 'first system' (figure 239) employed the principles commonly adopted by his predecessors, and marked no innovation. The curtain was short and protected by a demi-lune before it as well as by bastions on each side. The dimensions were so chosen that flanking-fire from musketry was available in all parts, for Vauban deplored excessive reliance on the protection afforded by artillery alone. In the more elaborate 'second system' Vauban utilized defence in depth: a second ditch and wall, flanked by two-storeyed gun-chambers (*tours bastionnées*) were erected behind outer works of the same type as in the first system. The low *tours bastionnées* commanded both the inner ditch and the outer bastions, so that even if the enemy forced his way upon the latter, his further way was still barred; and at the same time their thick walls and roof afforded a shield to the cannon in them impracticable for those mounted on the ramparts. Vauban's 'third system', of which few examples exist, was no more than a slight modification of the second.

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[1] A French saying of the time ran: *Ville assiégée par Vauban, ville prise; ville fortifiée par Vauban, ville imprenable.*

The engineering work involved in the intense fortification of the seventeenth century was an important prelude to the much greater development of civil engineering—first the construction of canals, then of railways—that came later. Vauban himself acted on occasion as a civil engineer; in 1686 he gave advice, which was adopted, on the construction of the *Canal du Midi* (p 467). Military engineers had to practise accurate surveying, to study soils and their properties, to excavate considerable ditches and construct earth ramparts, to organize gangs of workmen and the transport of materials. Though they worked for the state, their estimates were carefully scrutinized and their disbursements checked. In all this they anticipated the work of canal- and railway-contractors of future generations, so that the military engineer provided many techniques which could be readily adapted to peaceful purposes when the opportunity arose, and when capital comparable to that devoted to war was available.

VI. SCIENCE, TECHNOLOGY, AND WAR

The recurrence of warfare between states from the inevitable conflict of their policies, and the necessity for men to take service leading to suffering and death for reasons of which they understood little, were at an earlier phase of European history more calmly accepted as unavoidable elements in human destiny than they are now. In utter condemnation of war the Quakers stood practically alone, and though others deplored its wastefulness and horror, most men in all countries were comparatively sheltered from them and so felt little. Hence attempts to invent new destructive weapons, or increase the effect of those already in use, were not regarded with such distrust as in recent years: the scale of slaughter sought was, by modern standards, puerile. A new feature of these attempts, in the seventeenth century, was the endeavour to devote scientific knowledge more completely to military ends.

There were, for example, a very large number of works on practical mathematics and applied geometry published in the sixteenth and seventeenth centuries, most of which show, with illustrations, how their methods of survey (measurements of height and distance, and so on) could be applied to military purposes, particularly to the direction of artillery and of mining-operations [10]. Writers on gunnery often teach the rudiments of the same techniques, so that for this and other purposes (such as the calculation of charges of powder in proportion to the bore of the piece) the expert gunner was supposed to have some humble mathematical attainments. Accounts of battles and sieges, unfortunately, are rarely detailed enough to indicate how often they were required in practice.

The most obvious usefulness of science in war was, of course, in military medicine and surgery, where the French surgeon, Ambroise Paré (? 1517–90) had already shown the way. Military doctors have done much to develop preventive medicine and sound hygiene, but control of the epidemic diseases to which armies are peculiarly subject, and of the deficiency-diseases afflicting fleets on the high seas, was not achieved until after this period. As regards the manufactures devoted to war, science could as yet do little, since the chemical and metallurgical industries were still wholly empirical, and indeed governed to a large extent by traditional craft-knowledge: but the Royal Society, for example, showed a desultory interest in explosives and experimented on a number of different compounds. With regard to the mechanical sciences, however, the position was otherwise, for these had advanced with enormous rapidity to a very advanced position by the end of the seventeenth century. As mechanics is concerned with the motion of bodies, its application to the study of the flight of projectiles and the military problems of ballistics was obvious enough.

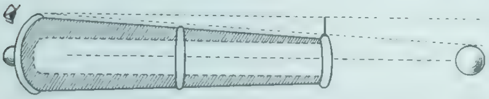

FIGURE 240—*The 'dispart' of a cannon. As the metal is thicker at the breech than at the muzzle, the line of sight along the exterior is not parallel to the axis of the bore. To correct this, the gunner stuck a piece of wood or straw to the muzzle with wax, to serve as a fore-sight.*

Aristotle had developed certain notions on the free motion of projectiles through the air; his ideas were well known, and considerably modified, in the later Middle Ages. The first to apply these general ideas specifically to the flight of cannon-balls and mortar-bombs was the Italian mathematician Tartaglia (1500–57). Among other things he accounted for the need to 'dispart' a gun (figure 240), he described the trajectory as a continuous curve, and he claimed (probably falsely) to have invented the gunner's quadrant. He asserted, on empirical grounds, that a gun attains its greatest range at 45° elevation, and he attempted as did many others after him to compile tables giving the range at any angle of elevation, the point-blank (0° elevation) range being known. All such endeavours were frustrated by lack of a reliable mathematical theory of motion, and of such concepts as force and acceleration.

The situation was far different when Galileo (1564–1642) enunciated the fundamental laws of motion, and went on to demonstrate in 1638 that a projectile, the air-resistance and other perturbations of its motion being neglected, describes a parabolic trajectory. On the basis of this demonstration he published the first well founded set of range-tables, for he assumed as did many other writers on ballistics until the early eighteenth century that in practice the effect of air-resistance on the flight of military projectiles was slight enough to be disregarded. More careful experiments showed this assumption to be false. The calculation of trajectories with allowance for the effect of air-resistance in reducing the velocity of the projectile was undertaken later by Huygens and Newton: the problem raises enormous mathematical difficulties.

In fact, however, these difficulties were less important than others arising from the state of technology. Neither guns nor propellants were powerful enough to enable long ranges to be usefully employed: and the behaviour of weapons was so unpredictable that calculation of mathematical trajectories was in fact irrelevant and pointless. With an imperfectly spherical shot, fitting loosely in a mere approximation to a true cylinder, at any range but the shortest the shot was distributed in a random manner over a large area about the target. Until the technology of firearms was much improved—as it was only by the development of machine-tools in the nineteenth century—the mathematics of exterior ballistics was a subject that the practical gunner could afford to ignore.

Nevertheless, guns were fired at gradually increasing ranges from the sixteenth century onwards, and there was some demand for instruments to be used for checking the accuracy of the gun's bore, for setting it horizontally on the ground, and for laying it upon the mark. The simplest was a quadrant with a long arm, inserted in the bore of the gun or mortar, showing the angle of elevation: when this had been found by trial-and-error, the piece could easily be relaid on the same mark. A plumb-bob level (or, later, a spirit-level) was employed to make sure that the axle of the gun-carriage was horizontal. More elaborate sighting-instruments were also made, some showing great ingenuity and beauty of workmanship (plate 25), but they can hardly have been of much practical utility. The real gunner trusted to experience, and had more faith in his eye and judgement than in a tangent-scale.

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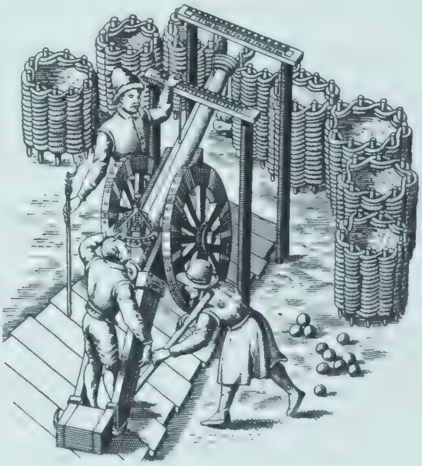

Laying siege-guns with the aid of clinometers and other instruments. Note the earth-filled gabions used to protect the guns and the wooden platforms prepared for them. The master-gunner holds a lighted linstock. Ramelli, 1588.

15

PRINTING

MICHAEL CLAPHAM

I. ADVENT OF PRINTING

THE development of typographical printing in Europe during the second half of the fifteenth century changed the character of western civilization. A man born in 1453, the year of the fall of Constantinople, could look back from his fiftieth year on a lifetime in which about eight million books had been printed: more, perhaps, than all the scribes of Europe had produced since Constantine founded his city in A.D. 330. It would be natural for such a man, seeing the stream of printed matter widening year by year, to attempt to trace it to its source; and equally natural, at a time when the normal pattern of technological change had not been studied, for him to seek the origin of printing in a single forgetive invention which could be precisely dated and ascribed.

Late in the fifteenth and early in the sixteenth century several writers took this path. They drew their information from the traditions of various printing-houses, either directly or through notes inserted in books by their printers, a practice which did not begin until book-production was already well established; and from this slight and partial evidence established legends that in time acquired the status of history. The resulting concept of a single inventor of printing, and the natural rivalry that developed between the supporters of Johann Gutenberg (*c* 1400–*c* 1467) of Mainz and Laurens Coster (fl 1440) of Haarlem, have not only led to some fabrication and much disingenuous interpretation of evidence; they have also tended to obscure the nature of the invention. Only recently have historians inquired exactly what was invented, analysed the techniques involved in early printing, and traced their separate origins.

The beginning of book-production in Europe as an organized industry can be identified with reasonable certainty. There was at Mainz a printing-office which was producing in 1447, and which within ten years had developed to a size requiring substantial capital and employing a number of men. More than fifty printed works are connected with it by the evidence of the type-faces used. Three men were principally involved in its development: Johann Gutenberg and Johann Fust (*c* 1400–*c* 1466) in its early years, and Fust's son-in-law Peter Schoeffer (? 1425–

1502) later. How far each contributed technically is unknown; it is not even certain that any of them invented any basic new process. Certainly some of their techniques were of older origin, and were subject to experiment in various parts of Europe at this time. Further, several had been practised in China, Japan, and Korea very much earlier, and though the connexion between the eastern and western technologies is not proved, circumstantial evidence supports it (p 380).

The process: its nature and background. Printing, for our purpose, may be defined as the multiplication of images by applying colouring-matter to a prepared surface and transferring it to a receptive material. The word includes not only typography, or printing from movable types, but also printing from undivided surfaces.

We are not primarily concerned here with decorative printing, but with the multiplication of images conveying ideas. Before analysing the techniques for doing so, it is worth recalling that their widespread development was closely connected with the European Renaissance. At a time of intellectual ferment and a broadening social structure which required easier means of communication, inventive minds were naturally working towards some means of recording and conveying thought less laborious than writing on prepared skins. But without a receptive surface capable of quantity-production there was little advantage in techniques for multiplying images: since a folio of 200 pages required the skins of about 25 sheep, writing was the smaller part of its cost. Thus the initial stimulus to further invention was no doubt the introduction of paper-making from the Islamic Empire to Europe early in the twelfth century. Given a reproducible material like paper, the idea of a reproducible image on it must have occurred to many minds; significantly, we first find signs of printing activity near the early centres of paper-making.

Whether crusaders, merchants visiting the great commercial centre of the Mongol Empire at Tabriz, or missionaries and travellers from the Far East, brought back rumours of the printed books of China as a further stimulus to invention, we do not know. There is no evidence that the art of typography reached Europe from Asia, though the establishment in Korea of a type-foundry and the publication there in 1409 of a book printed from metal types show an interesting parallelism of development. There are, however, strong indications that the idea of printing from a prepared surface came to Europe from the Far East, and the actual technique may have been imported.

The basic techniques. The transference of colour from the printing-surface to the receptive material may be effected in three principal ways. The colouring matter may be applied in viscous form to the raised parts of a partially excised surface, and transferred by contact under pressure to the receiving surface: this is called relief or letterpress printing, and is seen at its simplest when an engraved wooden block is dabbed with ink and a sheet of paper placed on top, rubbed down, and stripped off. The second method, intaglio or gravure printing, also uses a partially excised surface; the colouring-matter, in more liquid form, is applied all over, wiped off the raised portions and then transferred from the excised portions to the receiving surface, which must be absorbent and soft enough to flex some little way into the recesses under pressure (figure 241). The third method, lithographic printing, utilizes a flat printing-surface, parts of which are chemically prepared to accept and parts to repel the colouring-matter; but its invention falls outside our period.

Of the first two processes, relief printing is both older and incomparably more important in this period: it was the fact of a relief printing-surface being divisible into separate components that made possible typographic printing, and led ultimately to large-scale book-production. In comparison, the use of intaglio was small and with few exceptions confined to illustration, decoration, maps, and music printing (p 404).

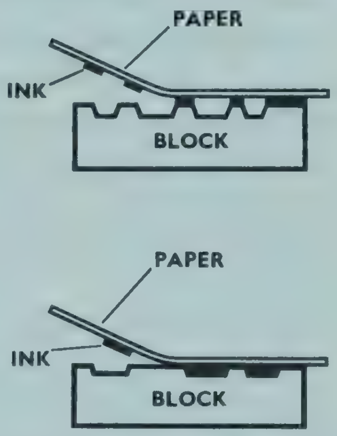

FIGURE 241—*Methods of printing.* (Above) *Relief or letterpress printing;* (below) *intaglio or gravure printing.*

Development of relief printing. The availability of paper was both a condition of the development of relief printing and a stimulus to it. The complete invention required also a means of preparing a printing-surface, a suitable ink, a means of transferring the ink to the paper, and the creative idea. The originator of the idea, however, and the place and time of its origin, are unknown and probably unascertainable. The use of excised wooden blocks for stamping patterns in plaster and for printing with dye on textiles appears to have been established in the Roman civilization, but since such blocks are highly perishable and generally in very simple forms, few survive and it is virtually impossible to date accurately those that do. One exception is the wooden Protat block, with its engraved picture and inscription, which was found near Dijon and dates from about 1370: it is too big for any sheet of paper then available, and was presumably used for one of the above purposes.

When such techniques were known, the idea of applying them to other than decorative purposes may well have occurred independently to many. The evidence suggests, however, that in practice the idea came to Europe from the Far East. Marco Polo in 1298 had described how the paper currency in Kublai

Khan's empire was printed by a seal dipped in vermilion ink; and the abortive attempt to introduce paper currency in Tabriz (1294) almost certainly resulted in some block-printed notes reaching the home towns of the big Venetian and Genoese colonies there. Twelve years later the missionary Archbishop John of Monte Corvino was writing home from Carambuc (Peking) of the biblical pictures he had had prepared for the instruction of the ignorant. These are casual examples of contact with the art; many more must have been unrecorded. At this period the trade routes into Asia by land and sea were active; southwards through Persia and northwards through Russia there was a regular passage of traders and missionaries to and from the Mongol Empire, where block printing was well established. There is evidence of its use by the fourteenth century as far west as Egypt. However, religious objection to the printing of the Koran prevented the technology spreading westward through Islam, as that of paper had done.

Apart from the paper money of China, the two commonest forms of printing which the traveller to the east might see would be playing-cards and religious charms, the forms in which we find the earliest European block printing. One of the first centres was Venice, whose contacts with the east were particularly close. In 1441 a decree of the Venetian Council laments that the art and mystery of making cards and printed figures has fallen into total decay, and prohibits the importation of such works whether painted or printed. Early in the fifteenth century, printing of this sort was clearly not a struggling new art so much as a lucrative industry. The cause of its decay in Venice is known to have been competition from south German towns. Playing-card makers—and since playing-cards at this time were cheap enough to be within the means of labourers they were probably printed, in outline at least—were registered in Augsburg and Nuremberg between 1418 and 1438, and are known to have operated on a considerable scale. Religious pictures were printed on a similar scale at the same period, in the same centres, and probably by the same men; but this activity became more widely diffused. The earliest surviving European religious prints are very simple productions. The figure of a saint is left in relief on a wooden block and dabbed or brushed with liquid ink; absorbent paper is placed on it and pressed into contact with a brush or a *frotton*, the leather-faced rubbing-pad used for much oriental printing. Later the technique becomes more finished, and inscriptions are cut below the figure: the earliest dated prints of this sort, the 1418 Brussels 'Virgin' and the 1423 Buxheim 'St Christopher' (plate 2B) are highly finished pieces of engraving compared with many extant specimens.

Numbers of these prints have been found pasted into writing-books in monastic libraries; and it is hard to suppose that the idea of producing a series of them in book form did not occur until after typographical printing was invented. In fact, however, though block-books became popular and were extensively produced in the second half of the fifteenth century, none of those surviving can certainly be dated earlier than about 1450. But it is characteristic of these books that one edition was copied from another, often by engraving a new block on to which a print of the old had been transferred, and probably some precursors of the numerous surviving *Biblia pauperum* were circulating before the first typographical books were produced.

Printing-ink. Religious prints and block-books throw light on the development of techniques for preparing and applying colouring-matter, and for transferring it from the printing-surface. The ink used for the early specimens was similar to that used by scribes, an aqueous solution of gum with either lampblack or the more finely divided ferric gallate in suspension as the pigment. Such an ink can, with skill, be brushed or dabbed evenly over a wooden printing-block, and will give a fairly good reproduction if a sheet of paper be laid on it and rubbed down carefully. This method has, however, several disadvantages. Though satisfactory on wood, a water-ink is difficult to apply evenly to metal surfaces, on which it tends to stand in globules; it is not readily transferred by simple impression, while rubbing-down is a slow process; and an absorbent paper must be used, so that the image shows on the reverse. The early block-books were therefore generally made up by pasting one-sided prints back to back.

A major contribution to the art of printing was the invention of an improved ink consisting of a pigment—lampblack or powdered charcoal for the normal black ink—ground in a linseed-oil varnish: it remained the standard printers' ink for more than four centuries. The inventor is unknown: Polydore Vergil, writing in 1499, attributed the discovery to Gutenberg, and a varnish-based ink was certainly used in the Mainz printing-office; but it is also found in some early block prints, and in printed fragments of Dutch origin and probably earlier date. The fact that boiled linseed-oil made a varnish of good binding and drying properties became known to the school of Flemish painters early in the fifteenth century, and the use of paints based on it for inking wooden printing-blocks would be a natural development wherever painters and engravers were working together—for instance, in the playing-card factories of Nuremberg and Augsburg. These factories may also have evolved the technique of applying oil-based ink which became standard among early printers: it was dabbed out thinly on a level surface with a pad made of damped leather stuffed with wool or hair, which in turn was dabbed on the printing-surface.

The press. The origin of the press as a means for transferring ink to paper is as obscure as that of printing itself. Its introduction depended on the availability of the new ink, which was viscous enough to allow the inked printing-surface, with the paper resting on it, to be slid into a press without blurring the impression. Given such an ink, experiments with a press were almost inevitable. Every sizeable household would have a linen-press consisting of a heavy base-board with two uprights carrying a cross-bar, through which a turned wooden screw pressed down a reinforced platen or top board sliding between the uprights. Similar presses (figure 242) were used for various industrial purposes, particularly in paper-factories for flattening the damp sheets (figures 114, 254). Anyone seeking to apply even pressure over a flat surface might well turn to this familiar implement, and several may have done so independently. Certainly by the time of the earliest surviving typographical fragments, about 1440, pressing had superseded manual rubbing or brushing down, though the more primitive technique continued in use for block-books into the last quarter of the century.

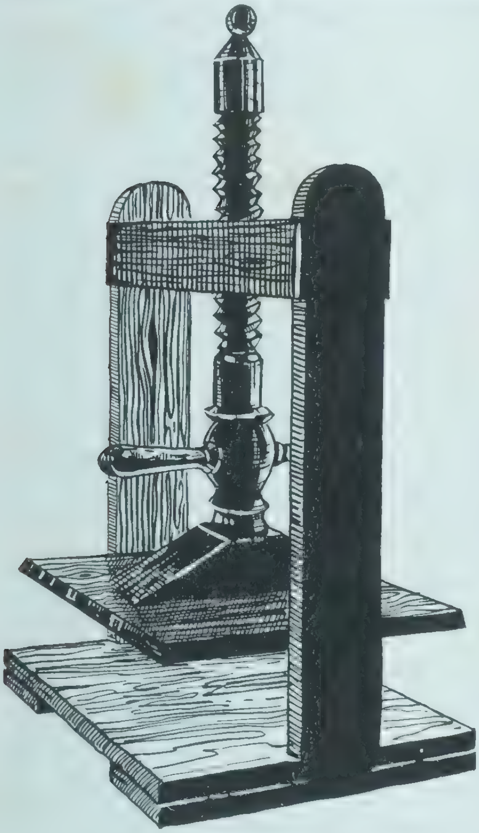

FIGURE 242—*A linen-press.*

In the year or two each side of 1450, when the Mainz printing-office was first printing books, the original screw-down press had probably been improved to make its action more rapid. It would be natural to increase the pitch of the screw, so as to speed the travel of the platen, and to incorporate a board sliding over the base-board on which the pages to be printed could be fixed, thus enabling them to be removed without disturbance for stripping and inking, and slid in again with a fresh sheet of paper and any soft backing-material necessary to get an even impression. Riccobaldi of Ferrara, in a chronicle published in 1474, speaks of the early printers achieving a production of 300 leaves a day; and an experiment in printing with a linen-press will satisfy anyone that a two-minute cycle of operations requires at least these improvements, and possibly some of the further ones described on page 389.

One point in the printing-operation must be noted. The well sized paper used for writing the manuscripts emulated by the early printers had too hard a surface to be printed sharply with the limited pressure available: it had therefore to be printed damp. The damping and subsequent drying increased the labour of printing; the sheets varied in dimension with their water-content, making it difficult to get accurate register when printing the reverse side or a second colour. The compensating advantages, however, were considerable; the impression was clean and sharp, and the pigment of the ink, trapped between the fibres of the paper as it shrank on drying, was securely held, giving an added depth of colour.

II. THE EARLIEST TYPE-FOUNDING

The invention of typography. By the mid-fifteenth century it can be taken that the art of printing, as such, was widely established—at least wherever playing-cards and religious pictures were being produced—probably with the press as an alternative to the *frotton*, almost certainly with a viscous oil-ink as well as one using a gum solution. The next milestone was the invention of typographical printing. The legends are familiar: one tells that Johann Gutenberg, a goldsmith of Strassburg and Mainz, invented movable types and the means of casting them in metal; that he turned to Johann Fust, a fellow goldsmith, for finance; that Fust having secured the technique broke the partnership and combined with his son-in-law, Peter Schoeffer, to exploit it. The other well known version makes Laurens Coster of Haarlem the inventor and Gutenberg an employee who absconded with the secret process.

We are concerned here not with personalities but with the way in which the techniques arose and were developed. There must have been some moment when the idea was first conceived that a type, the mirror image of an alphabetical letter, could be made in metal by a precision casting method: but we do not known when, where, or in whose mind it was; nor who first translated the idea into achievement. If Coster printed at all, there is no evidence of his contemporaries recognizing it; his name is first mentioned over a century after his supposed achievement, and no book bears his imprint. Gutenberg, in contrast, is far from shadowy: his extreme litigiousness has left his existence heavily documented, and he was distinguished enough to receive from the Archbishop of Mainz a sinecure to pension his old age. He too, however, failed to leave his imprint on any surviving book, an omission not in keeping with what is otherwise known of his character; and the clerk who drew up the customary rehearsal of his distinctions in the document, dated 1465, appointing him to the Archbishop's household, makes no mention of printing among them.

On the other hand, Gutenberg's claim to have made some significant contribution to the invention rests on a variety of evidence. A dubiously authentic document of 1436 refers to his partnership with Andreas Dritzehn of Strassburg and to the use of lead and a press. Another document, recording a lawsuit of 1455, claims that Fust had lent Gutenberg money to be employed in their common enterprise, while Gutenberg in reply refers to purchases of parchment, paper, and ink, and to the production of books. Another, dating from after Gutenberg's death in 1467, refers to the disposal of his instruments for printing. Most significant, perhaps, are the facts that Peter Schoeffer, Fust's son-in-law and partner, refers to Gutenberg as Fust's original partner in the invention of printing in the colophon of a book dated 1468—one year after the former's death and two years after the latter's; and that a sixteenth-century transcript of a document dated 1458, in the French Royal Mint, records Charles VII as having heard that Johann Gutenberg of Mainz was adept in cutting punches and characters, and as having decided to send Nicolas Jenson (d *c* 1480) to learn his art. It is not unlikely that Gutenberg and Fust were in fact independent experimenters in the production of type, who joined forces at the time when Gutenberg returned from Strassburg to his native Mainz about 1446.

But whether one or both conceived the idea of movable types, others certainly did so, probably independently. There survives a range of printed specimens, largely attributable to Holland—the so-called 'Costeriana'—some of which, though undated, are placed on circumstantial evidence earlier than the first productions of Mainz. Both in composition and type design they are cruder than the earliest Gutenberg–Fust–Schoeffer specimens; so much cruder as to suggest a more primitive technique of type-making. And in addition to the craftsmen experimenting with type-casting in Holland and in Germany, we know of one contemporary European experimenter working in southern France.

That many should work simultaneously but independently on the problems of typography is not surprising. With an established industry printing religious broadsheets and playing-cards from wooden blocks, every wood-engraver would learn to repair or correct the block by cutting out and gluing in an individual letter. Again, the economy of assembling up to ten separate blocks of one symbol each, rather than carving a complete block for each numeral card, can hardly have gone unnoticed. Wooden types were probably never used, except for large letters and initials, but, given the idea of the separate symbol or letter blocks, it would be natural to consider reproducing them less laboriously than by carving.

In particular, one can imagine the playing-card maker trying to use a single carved block for each suit as a pattern to press into clay or loam, thus giving a mould into which lead or tin could be cast. Compared with the precision casting of jewelry the technical difficulties would not be great. As a method of producing thousands of small letters, however, it was clearly unsatisfactory. Extreme accuracy of all dimensions is essential if a page of letters, necessarily of varying widths, is to fit together securely and give an even impression, and this could have been achieved with individual castings only by laborious hand-filing.

The key to the further evolution of type-founding, therefore, was the process of die-casting, using an interchangeable matrix in conjunction with an accurate metal mould. Whether or not the early Dutch printers or others anticipated it, this process was certainly first operated on a major scale in Mainz. The first works definitely attributable to the printing-office associated with Gutenberg and Fust—the 'World Judgement' fragment of a poem and the fragment of an astronomical calendar printed not later than 1448—use a type which, though large, is closely set and accurately aligned. It must have been cast in a mould of efficient design, since the same face was later used for the 36-line Bible, requiring a considerable production of type.

'Letter-cutting is a handy-work hitherto kept so conceal'd among the artificers of it, that I cannot learn any one hath taught it any other.' So wrote Joseph Moxon, author of the first full-length manual on printing (1683). We know a little now of sixteenth-century practice: but fifteenth-century techniques can only be surmised by reference to contemporary metallurgy (p 43), and to the appearance of early printing. The earliest Dutch types give rather rough impressions; they may have been cast in moulds impressed by a wooden punch in clay, loam, or one of the special compositions in use for intricate castings. Or matrices may have been made by pressing a wooden punch into lead just as it set; such matrices have been shown capable of casting satisfactorily more than sixty types each. Later, copper punches were used to strike lead matrices (p 392). It is possible, however, that the Mainz printers may have used steel punches initially: as goldsmiths they would know of their use in coining. Certainly the consistency—there is not complete uniformity—of letter design throughout their major works indicates an advanced technique and a durable punch and matrix.

Nothing is known of fifteenth-century type-moulds. Pierce Butler has conjectured that a pair of plates, L-shaped in plan, were slid together to grip type-sized matrices of various widths, but such matrices could equally well have fitted into the end of simple split moulds of fixed size.

The composition of the original type-metal is also unknown. Almost certainly, however, it was an alloy of tin and lead: the casting of this material was already highly developed among the pewterers (p 43).

III. AN EARLY PRINTING-OFFICE IN OPERATION

We may now seek to reconstruct the equipment and methods of working of a printing-office, say that of Fust and Schoeffer about the year 1450. The finishing touches were then perhaps being put to the Constance Missal, the earliest complete surviving book, and a start was being made on the great 42-line Bible whose 1700 folio pages are a masterpiece of both technique and design. The reconstruction necessarily contains speculative elements. The earliest printers were not anxious to divulge the mechanical nature of their process, and, even when the craft was established, its secrets had a commercial value which long kept them unpublished.

The early printing-offices were of necessity self-contained. Although in the experimental stages one or two men may have performed each operation in turn, there must have been considerable specialization of function soon after 1450, when more than one press was in continuous production. Paper would be bought; ink would be made periodically as required. The permanent sections would be the type-foundry, the compositors, the corrector, the pressmen, and—though the bookbinder would be an independent craftsman—a place where printed sheets were collated.

The work of the foundry consisted of making the punches, striking them into the metal used for matrices, and casting the type in the matrices, first, perhaps, constructing a number of moulds in which to do so. All operations except the completion of the type-casting would have to be done before the setting of any type, and the first stage would be the cutting of the punches. Each would be cut on the end of a steel, brass, or copper rod of rectangular section; and owing to the need to imitate all the ligatures and abbreviations of contemporary manuscripts, a set of matrices would run to more than 150 characters for each size of type, without allowing for replacement of breakages. Within the last century, the output of a skilled punch-cutter working on letters already marked out has been put between two and four punches a week, and the accumulation of the punches for each fount must have occupied the fifteenth-century designer and punch-cutter well over a year—perhaps more than two—even if two or three men were working continuously. Without precise measuring-instruments, there would be great difficulty in securing accurate alignment of the type from a series of hand-cut punches struck by hand into matrices, and there is no evidence on how it was overcome. Since, however, we know that a matrix could be of the same size and shape as a finished type, we may guess that the punch was originally a similar blank, on the end of which the 'line'—that is, the line at the foot of the small or lower-case letters—was lightly scratched. With this as a guide, the letter would be drawn in, and the metal round it and inside its outline carefully punched down and chiselled or filed away. The effect would be judged by taking impressions at various stages, perhaps—as in later practice—after blackening the punch in candle-smoke. On completion, the metal would be hardened, and the resulting punch would be identical in face with the type to be cast.

The next operation would be striking the punch with a hammer into a suitable blank of the softer metal used for the matrix. There would no doubt be considerable variation in the depth of strike, but this would not be a serious defect since the type as cast would in any case have to be brought to the right height by filing at the foot.

With the completion of a set of matrices, the preliminary work of the office would be done. The next operation would be typecasting. A single page of the 42-line Bible contains about 2750 letters; and at any time in its production there must have been a minimum of two pages printing, two more being set and corrected, and two more being 'distributed'—that is, being broken up again to individual types for replacement in the type-cases. For these six pages, allowing a very moderate proportion of type unused in the cases, about 20 000 individual types would have to be made. In the later stages of production, when six pages were being printed simultaneously, up to 100 000 types will have been in use at any one time.

In the last days before typefounding was mechanized, four centuries later, 20 000 letters would have been six or seven days' work for a team of two men, one casting and one dressing: but at this time, with a primitive mould probably needing to be taken apart after each cast, with a matrix which would often adhere to the type, with each letter having to be adjusted for height and probably filed down on three sides to get it square and to size, two men can hardly have produced more than 25 dressed types an hour. At this rate there would be two or three weeks of casting and dressing type before such a major work was undertaken, and over twelve months before the quantity ultimately required could be completed. The subsequent replacement of types worn down, damaged, or broken would probably employ one man continuously.

We can therefore imagine the foundry as normally employing at least two men, including one skilled punch-cutter. Of their product, we know little except the design of face, which has been exhaustively studied; but since in an occasional fifteenth-century book we find the impression of types lying on their sides, we can say that in height and shape they were not unlike today's four-sided prism, approximately one inch high (figure 243).

Of the way in which type was stored we lack contemporary evidence; but the Jost Amman woodcuts a century later (cf. figure 244) show that the type-cases—shallow trays partitioned for type-storage—still had compartments of approximately equal size. Presumably this obvious arrangement was adopted early on, and the compositors in Mainz stood before a single case, big enough to hold all the sorts in use. Of the other tools of the trade again we know nothing. The types may have been set into a primitive composing 'stick'. More probably, however, they were too irregular for handling in lines, and were set straight on to a wooden tray, about the size of the printed page, which could be wedged up tightly and transferred complete to the press.

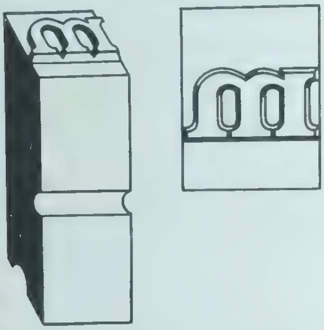

FIGURE 243—*Type: isometric view* (left), *and plan.*

The page would undoubtedly need much attention before it was ready to print. A century later, type came from the foundry so accurate in all dimensions that a page of several thousand letters could be held in a solid block, with a minute variation in the height of the printing-surface, by the pressure at side and foot of wooden wedges—'quoins'—driven against a tapered 'sidestick'. But the type of the 1450s must have needed careful wedging to keep each line firm and square on its feet. In books of this period the same letter varies in width and height: defective casting or damage when separating the type from the matrix must have meant filing down individual types at the top, bottom, or sides. No doubt the height, too, varied and needed adjustment.

Bearing this in mind, we can assess the speed of working. A nineteenth-century compositor on piecework would have taken three or four hours to set and impose a page of the 42-line Bible, using accurate type in ample supply and a precisely made composing-stick, galley (the shallow tray used to hold composed type), and spacing-material. His fifteenth-century counterpart can hardly have taken less than twice as long, using his highly irregular type and equipment, and a case in whose equal-sized compartments the more commonly used types would soon need replenishing: each page would thus take him about a day. There is bibliographical evidence that in its later stages the book was printed on six presses, each served by its own compositor or compositors, and it seems likely that at this time the composing-room strength was being increased from about three to at least six men.

The first stage of the compositor's work would be completed as each page was firmly wedged together and a proof taken for the corrector to the press, or 'reader'. A printer's reputation for care and accuracy has always reflected his reader's knowledge and acuity of observation: the fifteenth-century reader would normally be a scholar, and would combine with his work of correction the editing of the text. His method of operation has probably not changed much over the centuries; he would compare the original text with the proof, line by line and word by word, using the simple marks and instructions in the medieval scholar's tongue—*dele*, *transpone*, *stet*—which a conservative trade retains abbreviated or in full to this day. The corrected proof would go back to the compositor, who would loosen the type and make the alterations, and another proof would be checked before being passed for the press.

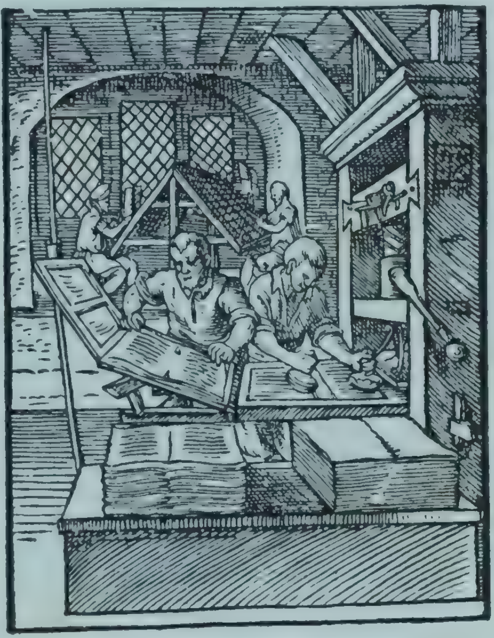

FIGURE 244—*The printer. 1568.*

The press used by the early Mainz printers cannot have been far removed from the linen-press. Its slow rate of operation, already mentioned, indicates only minor improvements before 1450: probably a tray in which the type could be wedged, inked, covered with paper and backing-material, and slid under the platen. About this year, however, an important improvement was introduced. This was the 'tympan', a frame covered with parchment on which the paper to be printed was fastened, and which was hinged—at first probably to the tray containing the type—so that the paper came down exactly level with the surface of the type. With this device a sheet could be positioned precisely in relation to the type, in spite of the irregular edges of hand-made paper, by pressing it on to 'press-points' which perforated the margins, leaving holes which were placed over points fixed in the appropriate position to give exact register when backing-up the sheet or printing a second colour. Such points have marked the margin of the 42-line Bible, whereas the earlier Constance Missal, whose register is in comparison a little irregular, was presumably printed by dropping each sheet on to the inked type, and repeating this process for the red printing and for both printings on the reverse: the technique may sound unlikely to achieve reasonably accurate registration, but it is still used successfully in printing-offices where proofs are taken on hand-presses.

About 1450, then, we can suppose the Mainz office to be adding tympans to its two or three original presses and installing three more. Each press would employ two men; one would affix the paper to the tympan, fold it down, place backing material on top of it, slide the assembly under the platen, screw it down, and, after a second or two, screw it open again. The second man would dab out ink on a stone slab, cover the ink-balls with a film of ink, and ink the type while the paper was being replaced. The press-room would also employ one or two men to hold ready the sheets of damped paper, damp further supplies for the following day, and hang up the printed sheets to dry. In addition, there might be one or two men gathering up the dry printed sheets and collating them ready for the binder.

The Mainz printing-office, then, in the early 1450s, must have been a considerable establishment. Our examination suggests a staff of about 25 men; at least 2 typefounders and 6 compositors, a reader, 12 pressmen and assistants, and a few others. It is thus not surprising either that the strain on the working capital of the partners was considerable, as the 1455 lawsuit suggests; or that there were men available to found the various other presses which started in the ten years before the sack of Mainz in 1462, and the numerous ones thereafter.

IV. DEVELOPMENTS: 1462 TO 1730

The improvements in the technique of printing between 1450 and 1730 cannot often be attributed to individuals or even to localities. Printing as an art became widely diffused. By 1500 it was established in twelve European countries; though, of nearly 40 000 recorded editions of books printed in that period, less than a third were produced outside Germany and Italy. By 1600 printing was being carried on in almost every country in Europe, and before 1700 at several places outside Europe, including the Americas. The art, however, retained its international character, recognized improvements in its implements and methods passing fairly rapidly from place to place. It is therefore convenient to examine the progress of the component parts of the process in turn, rather than to attempt an overall chronological survey.

Typefounding. Improvements in the technique of typefounding were rapidly effected. By the middle of the sixteenth century tools and methods had been developed that did not alter greatly over the next 300 years. Progress was aided by the recognition of printing as an art in itself, which enabled printers to dispense with numerous combined letters, known as 'ligatures', and overhanging or 'kerned' letters, which had been appropriate enough to the scribe's pen but added enormously to the labour of casting and composing type. The fount, originally 24 capital or upper-case and 24 lower-case letters, with 10 figures and about 10 marks of punctuation and conventional symbols, was at first supplemented by about 100 variant letters or ligatures, making a fount of up to 170 characters. Some ligatures, such as ff, fi, fl, ffi, and ffl are still used; and the diphthongs and certain ornamental combinations such as ſt, ct, and those containing the long ſ, were only gradually eliminated. The standard fount, however, was reduced to about 100 characters during the sixteenth century, in spite of the tendency in its last twenty years to admit the letters J and U to the roman 24-letter alphabet, a practice finally established about 1620 or 1630.

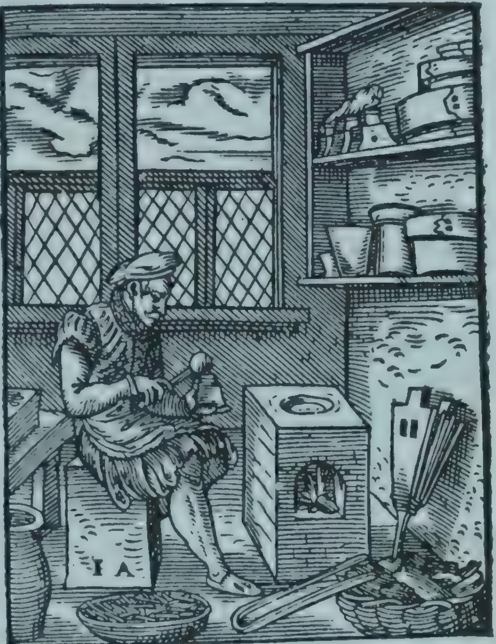

FIGURE 245—*The typefounder. 1568.*

A first brief account of typefounding appears in Vanoccio Biringuccio's *Pirotechnia* (Venice, 1540). Christopher Plantin, the famous Antwerp printer whose equipment survives there, published in 1567 *Dialogues françois pour les jeunes enfans* containing a simplified but fuller description. A year later the Jost Amman woodcuts illustrating Schopper's Panoplia, *omnium illiberalium, mechanicarum* etc. give us a picture of the typefounder at work (figure 245). We do not get a really detailed account of the typefounder's methods and tools, however, till 1683, when Joseph Moxon published the second volume of his 'Mechanick Exercises', describing a technique of typefounding which did not alter materially till well into the eighteenth century. Its development can thus be followed with some confidence after the *incunabula* period.

The technique of cutting punches and striking matrices changed little from about 1500 till punch-cutting machines were invented. Biringuccio, Plantin, and Moxon all describe the cutting of a letter on the end of a steel rod, which was hardened and struck into a sheet of copper to give the matrix. Moxon mentions the difficulty of positioning the punch exactly while doing so. He further describes the making of counter-punches, with which the unwanted metal inside and outside the letter itself is punched down; and the vice, files, and chisels which were the punch-cutter's main tools in his time, as no doubt 200 years earlier. It is difficult to explain why, since more technically advanced materials were known so early, the use of copper punches and lead matrices also survived. It is, however, recorded that a Dutch foundry was using them about 1500: the matrices are still preserved at Haarlem. In England, type-foundry records show lead matrices in use long afterwards: a set was included in an eighteenth-century sale.

The development of the mould before 1540 can be judged only from occasional impressions, which occur in early printed books, of the side of types pulled out in inking. These differ from modern ones chiefly in lacking the nick, which indicates to the compositor's fingers the right way up to place the type, and in being more roughly formed at the foot (figure 243). Only after several decades was the mould shaped to mark the foot of the type and so enable the tang, or unwanted metal solidified between the foot and the mouth of the mould, to be broken neatly away. Previously, types were apparently cast somewhat longer than required, sawn to length, and filed smooth.

Biringuccio in 1540 describes a mould of brass or bronze, consisting of two flat components sliding together and adjustable for letter-width. It uses flat matrices, which are held underneath the aperture of the mould by small screws. Such a mould might be capable of quite rapid production. The moulds illustrated by Jost Amman in 1568 are still further advanced: the mould shown in the type-founder's hand appears to be a hinged one, which is held closed in use (figure 245). Similar moulds on a shelf near him have a hole near the base, presumably for the transverse insertion of a matrix such as those close to his right hand. The types in a bowl beside him still have the tang attached, but it is not clear whether a break is marked: there is no sign of a nick. Amman, however, may have worked from out-of-date originals. Certainly the mould described by Plantin a year earlier was an elaborate compound construction, mounted in wood, held together by a bow-shaped spring, and containing various parts identifiable with those described by Moxon 126 years later, including a wire to form the nick and a 'break' at the foot; and similar features have been described in a French mould believed to date from the sixteenth century. It seems therefore that a mould not unlike that in use at the end of our period was developed soon after 1540.

The improvement of the mould gradually reduced the amount of manual work in the subsequent operations of typefounding. The earliest types, cast in makeshift moulds and separated with difficulty from the matrices, must each have needed two or three minutes of hand work. First they would be sawn to length, presumably in a simple gauge; then the casting-flash along the sides of the type would have to be rubbed off; and finally the surplus metal round the face itself would need trimming away with the file. In the fifteenth century it was the practice to rub away most of the shoulder, or flat top of the body supporting the face, to ensure that it did not pick up ink and print. Later, when more accurate moulds had almost eliminated any flash except for the tang at the foot of the type, which was marked to break off readily, the main operation of dressing was to run a plane over the feet. Since, however, the number of double letters had been reduced partly by introducing kerned letters, such as *f*, which overhangs its neighbour on either side, these letters had also to be trimmed under the kerns with a special plane, and the shoulders of other letters had to be left square to support them. Kerned letters were a small proportion of the fount, however, and the combined technical improvements in the mould, the matrix, and the type-metal made typecasting a comparatively rapid process; Moxon in 1683 gives 4000 letters a day as the product of a caster and dresser working together, with the aid of a boy to break off the tangs. However, in the following century a rate of 3000 letters a day was thought satisfactory, so he may have put the average too high.

The development of the metallurgy of typefounding is dealt with elsewhere in this volume (pp 43–4). Briefly, the original tin-lead alloy, similar to pewter, was replaced by an alloy in which lead predominated and which also contained antimony, tin, and sometimes other metals. The major step, probably taken early in the sixteenth century, was the incorporation of antimony: it conferred not only increased hardness, but also the attribute of expanding slightly on solidification, thus giving the type sharpness of face and accuracy of body.

Before leaving typefounding, mention should be made of its specialization into a separate trade. Although fifteenth-century printers generally made their own type, there is early evidence of interchange between them. Schoeffer's colophon to his 1468 Justinian implies his readiness to sell type; and the Ripoli Press cost-book records the purchase of matrices from one John of Mainz in 1477, and at other times purchases of founts of type and initials. Typefounding by printers continued to be the normal practice throughout the sixteenth century, and indeed the largest offices retained their foundries until mechanical typesetting transformed them; but there grew up between 1500 and 1600 a number of small offices relying on purchased type, and a class of typefounders who supplied them. The specialist typefounder was recognized before the middle of the century in Holland, which for the next 300 years was to have a high reputation for type and a flourishing export trade; and before 1600 typefounding was established as a separate trade in many European countries, including England.

This specialization, which supplemented the range of type of some offices while supplying others entirely, tended towards standardization of type-heights. At first it was only local, in places where a single foundry was able, or a group of printers was agreed, to enforce the convenience of interchangeable material. In spite of its obvious desirability, the difficulty of getting a printer to replace at great cost his existing stock of types for the sake of future benefits prevented such progress being made until national bodies began to interest themselves in the problem at the very end of our period. Sixteenth-century types certainly varied in height between 22 and 27 mm, and if by 1730 there were considerably fewer type-heights than printers, there were still more than there were countries practising printing.

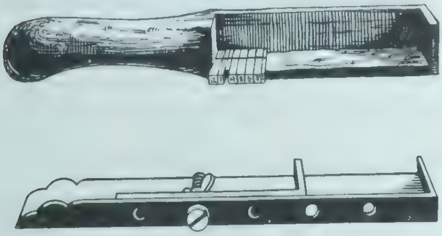
FIGURE 246—*Composing sticks.* (Above) *Fifteenth-century;* (below) *seventeenth-century.*

The compositor's equipment is simple, and has varied little except in material over the past 500 years. His personal tools are a bodkin, a pair of tweezers, and one or more composing-sticks. Plantin's compositor in 1567 holds in his left hand a wooden composing-stick (figure 246) and sets letters into it till he has got a full line, which he then transfers to a galley; and a block in a book published in 1507 shows a stick being used by a compositor in just the same way as his successor used the iron 'stick', with one side sliding to adjust the length of line, which came into general use at the end of the sixteenth century and has altered little since.

Apart from these personal tools, the main equipment of the composing-room consisted of the cases for storing type; the wooden frames on which they were rested; a flat surface on which the type was finally 'imposed', that is, made up into pages, spaced to give the correct margins, and locked up into a metal frame or 'chase'; a supply of chases, wooden spacing-material, and head- and side-sticks narrower at one end than the other; and quoins (p 388) to hold the assembly of pages, or 'forme', firmly in the chase.

The development of the type-case before Moxon's time can be only sketchily reconstructed from the surviving illustrations of printing. The large single sloping case with about 160 divisions shown in a woodcut by Amman was presumably the earliest approach to the problem: it worked adequately so long as a printer possessed only one or two founts, but it was too large readily to move about when a variety of type sizes and styles became normal. Much smaller cases appear in Stradanus's picture of a printing-office (figure 247), dating from about 1590: but this is inaccurate in detail, and serves only as an impression of how a small and not very up-to-date establishment was laid out and operated. The important development was towards a case in which the letters were arranged with the most commonly used ones grouped centrally, and in which the size of the compartments was related to the frequency of each letter's use. It is not known who first departed from the equal-sized, alphabetically arranged compartments. It can be inferred that Plantin started by laying his type alphabetically in the cases, which may therefore have been the common usage in the mid-sixteenth century. By 1683, when Moxon wrote, the modern style of case had been established so long that he did not comment on its novelty. In the intervening period there are few illustrations of printing processes, and no surviving type-cases can be placed before 1700 in their present form. Clearly, however, some time after about 1550 there came into general use a pair of cases, the upper case (that is, the one placed higher on the sloping frame) containing the capital letters and figures, arranged alphabetically, in its left half, and either

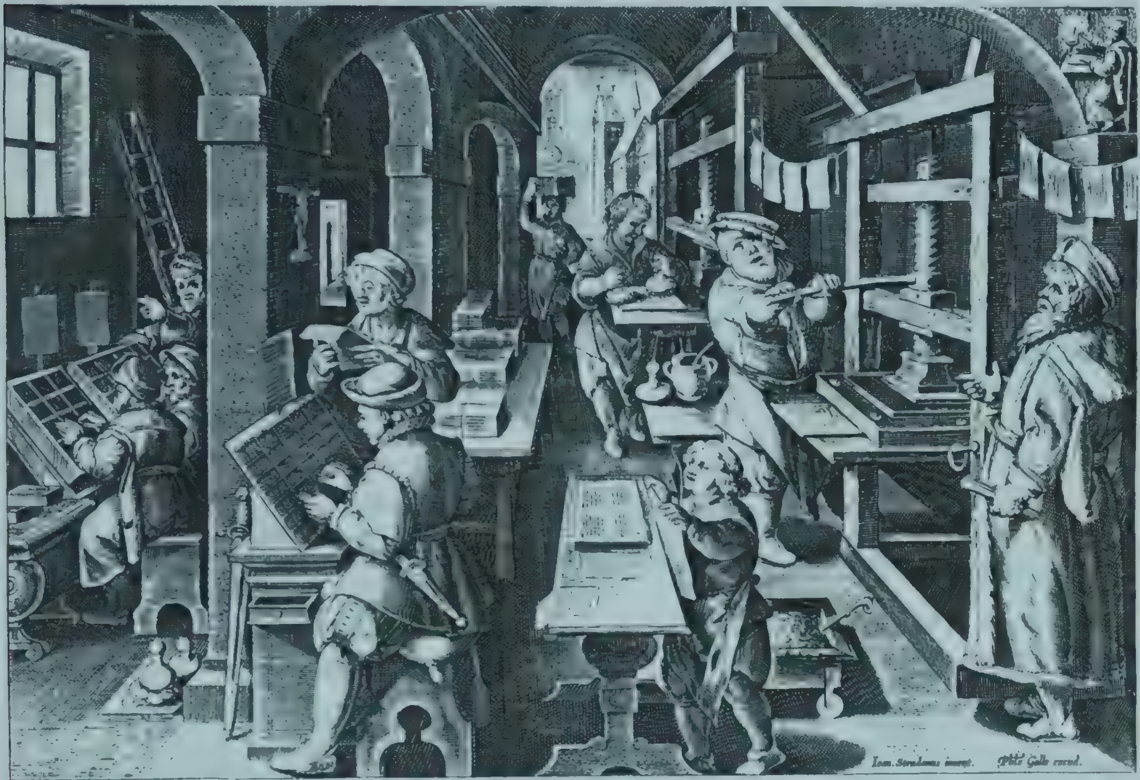
Ioan. Stradanus invent.
Phls Galle excud.

FIGURE 247—*A sixteenth-century printing office.* (Left to right) *Composing the type from copy; correcting the type in the forme; inking type and assembling printed sheets; pressman at work. Note printed sheets drying. From Stradanus,* c *1590.*

the small capitals or the italic capitals in the right half; and the other case containing the minuscule letters now known as 'lower case', arranged according to the frequency of use, which varied somewhat with the language (figure 248).

Little other notable change occurred in the composing-room before 1730. The frame on which the cases rested came to incorporate racks below, in which additional cases could be stored. The imposing surface was no doubt made of stone in the earliest development of printing, as being readily ground to give a large flat surface, and it was still stone—marble, Purbeck, or some other fine-grained variety—in 1730. The chase, a wrought iron frame inside which type-pages could be locked up for printing, was probably developed between 1450 and 1470, as type became accurate enough to hold in blocks by side and foot pressure alone. By 1499, when the first representation of a chase appears,[1] it has a cross-bar, so that one folio page, or a pair of quarto pages, can be unlocked for adjustment without disturbing the rest of the forme (figure 249). By 1550, when printing in octavo and smaller formats was normal, chases divided into four by cross-bars at right-angles were also in use. The wooden spacing-material and the head-sticks, side-sticks, and quoins were not materially altered from the earliest days until within living memory.

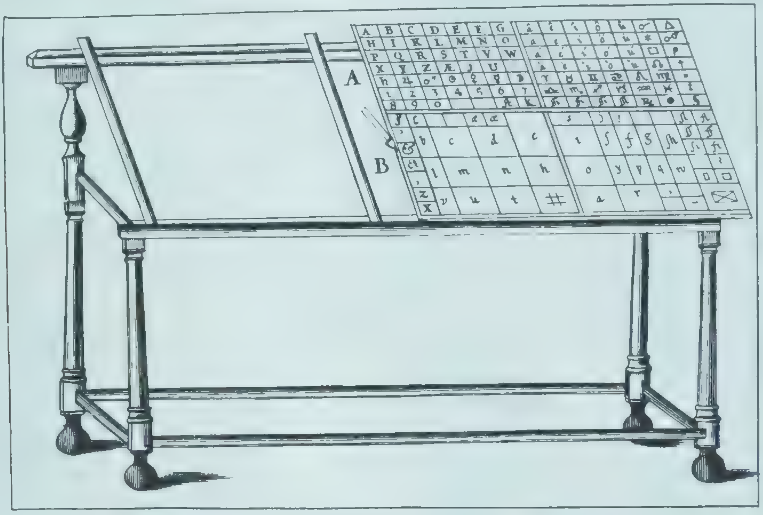

FIGURE 248—*A pair of cases. After Moxon, 1683.*

The press and its equipment. After the type-mould, the press is the most important mechanical device in printing. We have no exact knowledge of its development from the simple screw-down wooden press during the fifteenth century, but thereafter it can be followed from numerous illustrations and from the descriptions of Plantin and later writers.

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[1] In *La grãt danse macabre.* Lyons, 1499–1500.

The experiment of printing a page of type in a linen-press helps in reconstructing the early stages of development. First of all, the page cannot be inked or covered with paper while under the platen of the press, nor can it be slid in after inking without risking displacement of the type or paper unless it is firmly mounted on a slide which can be introduced into the press complete. It is then found difficult, inserting the slide at random, to get the page centrally under the screw of the press, failing which the platen tilts and applies pressure unevenly; rails are therefore introduced to guide the sliding bed, and the fixed bed is extended to carry them clear of the platen, where the page can be inked. By marking the slide the page can now be centred; but as the screw is held vertical only by passing through the top cross-bar, usually called the 'head' or 'summer', and by the guidance of the side members or 'cheeks', some wobble may occur at the point of impression. The screw is therefore made to pass through a lower member, the 'till' or 'shelf', below the bar that turns the screw. This stage of development can be seen in the Stradanus illustration, the presses in which are more typical of 1490 than of 1590 (figure 247).

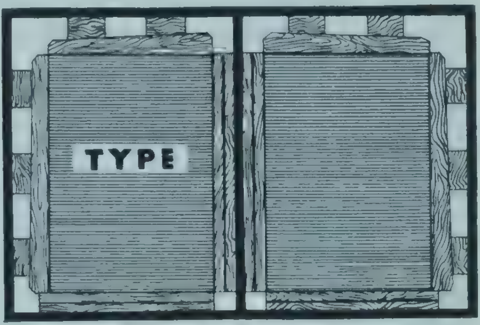

FIGURE 249—*Two-page forme, showing chase with one cross-bar, wooden furniture, and method of locking up with wedges (quoins).*

The spread of printing throughout Europe in the two or three decades each side of 1500 brought many new minds to bear on its technical problems. Within a framework of established practice, new experiments would be tried wherever printing-offices grew up, though the major items of plant, particularly the presses, would continue in use for many years. There would thus be—as today—differences corresponding to a century's development between the newly established, progressive, and highly capitalized concerns and the old-fashioned ones or those lacking resources to buy new plant. Indeed, to illustrate the next stage in press-design, we turn to a woodcut used about 1507 by the great Parisian printer Jodocus Badius Ascensius[1] (figure 250). The French contributed particularly to the design of the press at this period, and the *Prelum* [press] *Ascensianum* is probably typical of the most advanced practice in the early sixteenth century.

It shows clearly the principal differences between what may be called the improved linen-press and the wooden printing-press which, though refined in detail, was not fundamentally altered until the eighteenth century. The bed has been made to run in and out on rails; these are not visible, but clearly the bed can be made to travel by means of a handle and winding-gear, or, in the language of the trade, a 'rounce' turning a 'spit' on which is mounted a 'barrel' to which are attached the 'girts' or winding-straps. This woodcut shows a feature that does not appear in the only known earlier picture of a press, the *Danse macabre* woodcut mentioned above (p 396); namely, the 'hose', a hollow block of wood through which the screw passed, and to which the platen was attached. This picture shows it hexagonal, though a square shape later became standard; it passes through an hexagonal hole in the till. The function of the hose was to prevent the platen from twisting as it was lowered, particularly at the moment of impression, and the platen was suspended from it instead of from the screw. It seems here to be fixed rigidly to the platen, having probably developed from the socket in which the base of the screw is held in the press that Stradanus illustrates.

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[1] Badius (1462?–1535) was Flemish by birth, but worked for much of his life in Paris.

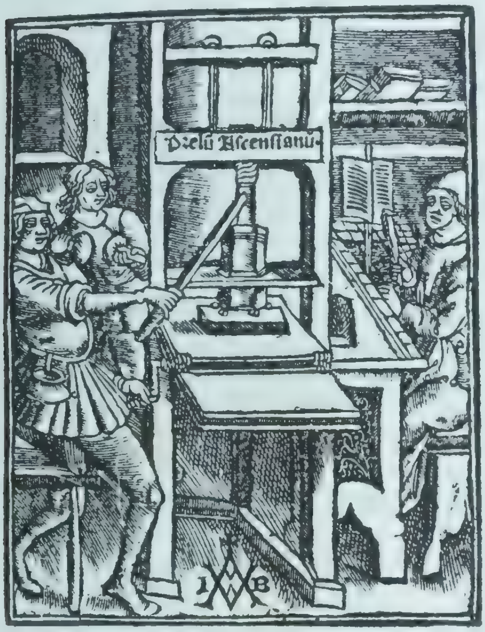

FIGURE 250—*The printing-press of Jodocus Badius Ascensius, used as his device. From the title-page of a book printed in Paris in 1507.*

The tympan, first introduced about 1450, is also visible in Badius's press, as a hinged frame attached to the bed on which the forme is placed. By the middle of the sixteenth century at latest, and probably as early as this illustration, it had developed into an inner and an outer frame, between which was a blanket or other soft material replacing the original loose backing.

Two points about presses of this period should be noted. First, the platen is small, only large enough to print half the forme at once, since with the simple screw-mechanism even the strongest pressman could get only enough pressure for about 240 sq in. Secondly, there is no counterweight to lift the platen after printing.

The minor tools of the pressman are visible in this and the other illustrations; they did not change materially before 1800. The type was inked with a pair of 'ink-balls', the leather covers of which were freed from grease and made supple by long pickling in urine, then carefully stuffed with wool; their basis was a cup-like stock and handle turned from beech wood. The ink on the inking-slab was spread with a flat knife or 'slice', and rubbed out thinly with a wooden 'brayer'. Nearby there would be a trough in which to damp the paper, and a press in which to store it. There would also be a lye-trough in which to wash ink from the forme: it can be seen in the right foreground of the Stradanus picture (figure 247).

Badius reproduced several other presses. In 1520, a more heavily constructed model is shown, with cheeks fully 6 in thick, and the barrel of the screw 8 or 9 inches in diameter; it has a square hose instead of the hexagonal one. Its most notable feature is that instead of a head with the screw passing through it, and a higher transverse member or 'cap' surmounting the cheeks, there is a single massive top member, from which two columns rise to the ceiling to ensure stability. This design was not generally adopted, but later presses were usually designed for greater rigidity.

The Jost Amman woodcut of 1568 (figure 244) shows a further refinement of press-design, the 'frisket'. This was a frame covered with parchment or strong paper, hinged inside the tympan, having the areas to be printed cut out. Its purpose was both to retain the paper in position against the tympan, and to protect the blank areas from contact with any spacing-material that might accidentally be inked. The frisket is first mentioned in 1587, but it must have been used a century earlier. If a pressman did not cut out the printed area accurately, or allow for the play of the hinges, the type might bite on the edge of the parchment, leaving the edge of the page impressed but not printed on the paper below. Such frisket-bites occur in the *Speculum vitae Christi* of 1487, but are uncommon in fifteenth-century books, so it is probable that some other device—perhaps tapes stretched across the tympan—was generally used to retain the paper until about 1500.

No hose is visible on Jost Amman's press, but this is probably a mistake in drawing, since the curved stays from the four corners of the platen no doubt run to the corners of a square hose passing through the till. This method of holding the platen horizontal and preventing it from twisting was by then well established, and is clearly seen in an English press illustrated about 1548; this differs from the Amman press only in having a large square hose and a longer, curved, metal handle. Such a handle became the established form. Its springiness eased the jerk on the pressman's arm when the platen was pulled down, and its rebound when released helped to raise the platen.

Two other points should be noted. First the type bed is clearly no longer the flat wood of the earliest presses, but the polished stone slab, bedded with plaster or bran into a shallow wooden box, the 'coffin', which was later adopted universally. Secondly the system of press-points on the tympan is plainly reproduced for the first time.

With these improvements, the press had completed the most important stage of its development within our period, and it is probable that there were in Europe at the end of the seventeenth century many presses similar to these models of 150 years earlier. A copper plate was being used as backing for the wooden platen before 1567, and towards 1700 brass or iron gradually replaced wood for making the screw, the rails on which the bed ran, and various smaller parts; but the first significant variation in design was not made till the early years of the seventeenth century. Then Willem Janszoon Blaeuw (1571–1638), the Dutch cartographer who as a young man worked with Tycho Brahe on his mathematical and astronomical instruments, and may have shared in his printing activities, introduced what became known as the Dutch press (figure 251). This differed from its predecessors in two ways. One was a minor improvement to the winding mechanism, enabling the girts to be adjusted more rapidly. The other was a radical alteration to the hose, which can best be described by comparing the Blaeuw press with the final version of the 'wooden' press (figure 252). In the latter, the hose is a long wooden box, which encloses the spindle from just below the bar to about 6 in above the platen, where it terminates in a metal cup with a hook at each corner. From these, the platen is suspended by cords running to each of its corners, while the hose itself is hung from a groove in the spindle just below the bar, into which there fit two slides inserted through slots in the side of the hose. The toe of the spindle, passing through the hose, rests in a metal cup at the exact centre of the platen, which is further reinforced by an iron plate below it. When the bar is pulled over by the pressman, the screw at the top of the spindle forces it down, carrying the hose and platen with it: the former is prevented from twisting by the square hole in the till.

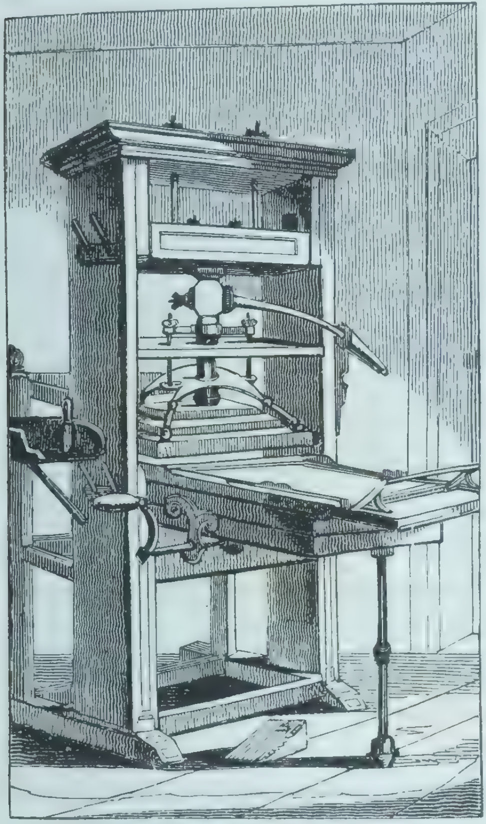

FIGURE 251—*The Blaeuw or Dutch press.*

In the Blaeuw press, instead of this hose-mechanism the spindle passes directly through circular holes in the till and in a metal plate below it from which the platen is suspended, this plate in turn being suspended from a groove on the spindle by a yoke carrying at each end a square bar passing through a separate hole in the till. This arrangement was perhaps slightly easier to make and to adjust than a well fitted box-hose; certainly it was immediately adopted as an improvement in the Low Countries, became almost universal in its use there,[1] and was exported to, or copied in, other countries. The first press to reach North America in 1639 was of the Dutch type. Moxon in 1683 praised the excellence of these presses somewhat extravagantly, contrasting them with the traditional type then generally in use; but, though later writers followed his encomiums, most printers in England and many elsewhere in Europe continued to prefer the square-hose model.

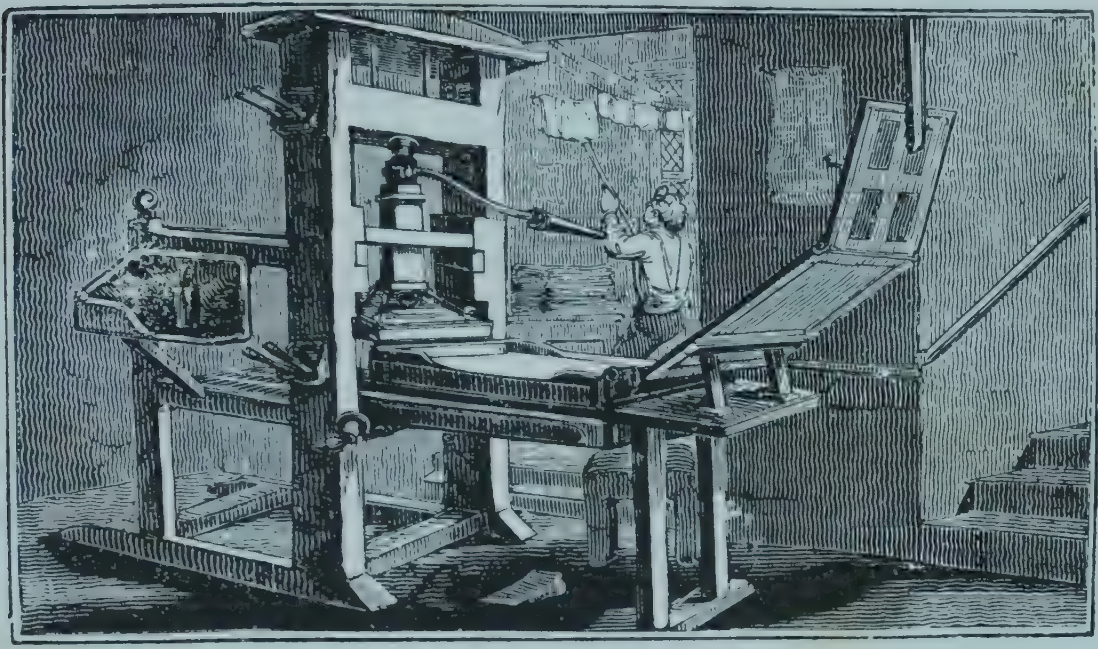

FIGURE 252—*The improved wooden press.*

V. STATE OF THE ART ABOUT 1730

It may be easier to appraise the progress of the art if the working of a printing-office at the beginning of the eighteenth century is briefly described. For this purpose we must suppose ourselves to be looking at an office large enough to produce its own type on a substantial scale: an establishment such as that of

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[1] The presses preserved in the Plantin–Moretus museum at Antwerp are early versions of the Blaeuw press.

Plantin and Moretus at Antwerp, or of P. and J. Blaeuw in Amsterdam; or one of the great institutional offices—the *Imprimerie Royale*, the *Stamperia Vaticana*, or the Clarendon Press at Oxford, which, under Dr Fell, had recently begun to provide its own type.

In such places the process started with the letter-cutters. They drew the letters on the end of steel blanks, punching down, graving or filing away unwanted metal; then hardened the punches and struck them into brass or copper matrix blanks about 1½ in long, ¼-in thick, and varying in width to suit the size of the letter. They then filed away any metal bunched at the side of the impression, and adjusted the dimensions of the matrix so that the letter would fall in exactly the right position at the bottom of the mould, after which the matrix was proved and handed to the caster.

Each caster sat beside a small furnace containing molten type-metal. In his left hand he held the mould: it was a complex unit, made of steel or brass and cased in wood, its two main members held together with a spring clip and positioned together by male and female gauges. Cut in one member and closed by the other was the adjustable cavity in which the type was cast, with a marked throat between the orifice and the foot of the type to allow a clean breaking away of the tang; with one or two wires let in at the side of the body to form the nicks; and with a hook at each side of the orifice to help to dislodge any type that stuck to the matrix. Into this mould the caster poured metal from a ladle picked up in his right hand, giving the mould a sharp twist and shake at the moment of pouring so as to drive the molten metal into every corner of the face: this dexterous motion, which varied according to the letter cast, comprised his main skill. After leaving it a second or two to cool, he opened the mould and threw the type, tang and all, on to a sheet of paper beside him. His output of cast types was between 2500 and 4000 a day, according to size and the difficulty of casting.

The next process was traditionally done by boys, who broke off the tangs, rubbed down the sides of the shank on a flat stone, and passed the type to the letter-dresser. He set up a line of types, examined it for defective castings, wedged it firmly in a 'dressing-stick', scraped with a knife first down one side of the line and then down the other, and finally, holding the line with the feet upwards, cut a groove along the centre of the feet with a plough, thus removing all trace of the broken-off tang. The finished types were then counted into the quantities of the 'founders' bill', a carefully calculated table giving the numbers of each letter required for a fount of a given size to print a particular language; and stored or passed to the composing-room.

The compositors at this period normally worked under a piecework system of elaborate but well understood conventions, and for this purpose were organized in 'companionships', each appointing its own 'clicker', whose main duties were to record the division and performance of the work and share out the earnings. To each companionship the master printer or his overseer gave out the copy to be set, the instructions, and the type—occasionally new type from the foundry, more commonly pages which had been printed and had to be distributed to the cases before re-use. Enough lines having been set for a sheet (two to sixteen pages, according to the size of book), they were made up in pages, laid out on the stone imposing-surface in the order required to bring the pages in sequence when 'backed-up' (that is, printed on the reverse side), and imposed into formes by dressing with wooden furniture to give the correct margins and by locking up with head-sticks, side-sticks, and quoins.

The formes were next proofed, and the proof-sheets sent with the copy to the reader's closet, where they were checked, marked with corrections, and returned to the composing-room. The formes were then unlocked and minor alterations made by changing letters or spaces in the imposed forme, while pages needing major alterations were tied up, lifted out, and reset line by line in the composing-stick. After a further proof—the 'revise'—and final correction, the forme went to the press-room for printing. About the same time, the paper was damped by dipping a number of sheets in water—every fourth, sixth, or eighth according to the thickness and hardness—and stacked under heavy boards until the moisture was fairly even throughout the pile.

The pressmen worked in teams of two, taking it in turn to do the heavy work of running the bed in and out and pulling the press, and the skilled work of dabbing the ink evenly over the pages. One man, having spread ink on the ink-block with the slice and rubbed it out well with the brayer, took his ink-balls from the rack, dabbed them on the ink, and rubbed them together with a circular movement so as to distribute the ink evenly over the surfaces. He then inked the pages of the forme in turn, occasionally rubbing his ink-balls together to redistribute the ink. The other man, who had meanwhile placed a sheet of paper on the press-points fixed to the tympan, and closed the frisket over it, then brought down the tympan, paper, and frisket on to the surface of the inked type with his right hand; gripped the rounce with his left and turned it to bring the first half of the bed under the platen, pulled over the press-handle with his right hand, moved the second half of the bed under the platen, pulled again, and, releasing the press-handle so that it sprang back and lifted the platen, moved the bed out and lifted off the tympan assembly. This cycle of operations continued until all the paper issued had been printed on one side, after which the sheets were printed on the reverse, hung up to dry, and finally collated by the warehousemen and sent to the bookseller or the bookbinder. Meanwhile, the worked-off forme had been washed with lye and sent back to the composing-room for the type to be distributed.

Notwithstanding the laborious double-printing of each sheet, and the difficulty of inking a large forme evenly, two good pressmen would print up to 250 sheets an hour on one side of the paper; say 3000 sheets a day in an office which—like Plantin's—worked from 6 a.m. to 8 p.m. in summer and from 7 a.m. to 9 p.m. in winter. These maximum outputs, however, are not to be compared with the 300 sheets a day which the earliest printers were proud to have achieved; for the average printing in 1700 was greatly debased in quality from that of the astonishing folios turned out at Mainz, on crude appliances but with devoted craftsmanship, two and a half centuries earlier. It is noted that, for large works of the highest quality, production might well fall below 1000 sheets a day even at the end of the sixteenth century. We may conclude that, for a given standard of work, all the improvements tending towards quicker press-work—more even type more rigidly held, improved operating technique, and a much more powerful and accurate press—had raised the productivity of the press by a factor of three, or at the most four, since the days when the first Mainz printers, their plant established and its processes well tested on a smaller book, felt able to embark on so great a work as a printed Bible.

VI. ILLUSTRATION, DECORATION, MAP AND MUSIC PRINTING

Turning from typographical printing to illustration and decoration, we are in a field where technique may vary markedly with the individual artist or with local tradition. It is therefore difficult to generalize, and impossible to trace a consistently developing technology; the metal-engraving processes particularly are capable of numerous minor variations few of which are ever superseded, in that the particular artistic effects they achieve may at any time commend them for re-use. The history of art being well documented, it is necessary here only to outline the main techniques used up to 1730.

Illustration printed in relief. The early woodcuts have already been mentioned. They were used for textile-printing early in the Middle Ages and perhaps in the later Roman Empire. In the medieval guilds, wood-cutters were grouped with carpenters; and their products were simple carvings with knife, gouge, and chisel on the plank—that is, on pieces sawn in the direction of the grain—of fine-grained woods. At first it was necessary to use resinous wood which would not swell or crack through absorbing moisture from aqueous inks, and cherry was considered the most suitable. Later, with the oil-varnish inks of the fifteenth century, apple, beech, pear, and sycamore were also used. Box, a harder and finer-grained wood, later to become the standard material, was widely used well before 1550, and the delicacy of some late fifteenth-century Venetian woodcuts suggests that it may have reached Italy earlier, from Turkey, its principal source.

Long after box came into use as a plank wood, the practice of cutting and planing it across the grain was developed, thus facilitating the use of white engraved lines on a black background. On the end grain very fine lines could be engraved with equal ease in any direction, and the metal-engraver's tools, particularly the graver or burin, could be employed. When this technique of wood-engraving was developed is uncertain, but it probably originated in eastern Europe at the end of the seventeenth century, and is certainly found in some Armenian books printed in Constantinople early in the eighteenth.

Relief blocks were also cut in metal, perhaps as early as the first European woodcuts. Lead, brass, and iron are all mentioned in the fourteenth and fifteenth centuries, but copper was probably the commonest medium. Since the cutting away of large areas of metal was laborious, the early metal relief blocks tend to be of the engraved style, with white lines on a black background, rather than the woodcut style of black lines on white; and to relieve the solid black they were often stippled with punches bearing various dots and ornaments, thus yielding the prints in the *manière criblée* which are characteristic of later fifteenth-century engraving.

Relief-printed blocks were combined with type early in the history of book-printing. The Fust–Schoeffer psalter of 1457, the first book dated by its printers, had ornate initial letters printed in two colours, and wooden or metal blocks were often subsequently used for initials, ornamental borders, head- and tail-pieces, and other large-scale decoration, while for smaller repetitive ornaments the type-casting process was employed. Wood- or metal-cut illustrations in mainly typographical books became common in the 1460s, following the lead of Albrecht Pfister of Bamberg, and soon assumed a special importance in technological history by enabling diagrams, plans, and maps to be incorporated in the text. Early examples of these are the astronomical and mathematical diagrams used by Ratdolt at Venice in the 1480s, and the woodcut maps which, after a first appearance in 1472, illustrated numerous early editions of the ancient geographers.

Woodcut blocks were also used in the fifteenth century to print music, though the earliest example, printed in 1487, is antedated by books containing crude attempts at music type. The design, casting, and composition of movable types to print simultaneously the staves and the notes are, however, exceedingly difficult: the problem was first mastered by Oeglin, of Augsburg, in 1508, though Petrucci of Venice had produced in 1501 an effective system of types requiring two impressions. Meanwhile woodcut music was used for odd phrases in typographical works until much later.

Intaglio printing. The arts of engraving and etching were developed for ornamenting metal surfaces centuries before the availability of paper engendered the idea of printing from them. That this idea coincided in time with the widespread circulation of woodcut prints and with the inception of typography demonstrates the tendencies leading to the rapid development of printing.

Engraving on precious and semi-precious metals has been practised since antiquity by goldsmiths, using a burin to engrave the line and a scraper to remove the burr which curls out on each side of the furrow as the burin is pushed forwards. The simplest form of intaglio print is made by taking such an engraved plate, dabbing ink all over it until every furrow is filled, wiping the ink from the surface, and then rubbing down a sheet of damped paper which sinks into the furrows and picks up the ink remaining there. A line-engraving of this sort in 1446 is the earliest dated one, but its engraver was one of a group working in Germany and the Netherlands about this time, and the earliest engravings of another, the 'Master of the Playing Cards', are probably a decade earlier.

The technique appears to have developed independently soon afterwards in northern Italy, where its first known exponent, Maso Finiguerra of Florence, was working about 1450. It was closely linked with *niello* work, a goldsmith's technique in which lines are engraved on a metal plate and filled with a preparation of metallic sulphides (vol II, p 480). Its original object was to produce a burnished plate bearing an inlaid design in black; but the practice arose of taking a sulphur cast of the engraved plate which, if blackened and rubbed to expose the ridges corresponding to the engraved lines, formed an equally effective plaque. We do not know whether paper was first used to take a proof of the plate by intaglio, or of the cast by intaglio, or of the cast by letterpress: a particular *niello* may be found as plate, or as cast, and in all three sorts of proof. Nor is it known when engraved plates were first made in Italy solely for the taking of prints. The earliest Italian engravers were, at all events, primarily goldsmiths, and their German predecessors may have discovered intaglio printing by the same route.

Three other main forms of engraved plates for printing were used before 1730; dry-points, etchings, and mezzotints. In dry-point work, instead of a burin being pushed forwards to incise the line, a pencil-like steel point is drawn across the plate, leaving the burr all to one side of the furrow, where it is usually left to retain a greater volume of ink and to soften the line. Only a small number of perfect prints can be achieved before the fragile sliver of metal is flattened, so that the technique was not used extensively for book-illustration, maps, or music; and in our period its use was limited to a handful of artists, including, however, two of the greatest. After some early prints by an anonymous German master about 1480, Dürer (1490–1538) used dry-point for three prints early in the sixteenth century. The process was combined with etching by Andrea Meldolla (1522–82), about fifty years later, and more notably in the mid-seventeenth century by Rembrandt (1607–69).

Etching, too, was originally used to ornament metal, and was practised by armourers in the fifteenth century. They reduced the labour of engraving by dabbing a coating of gum, resin, and wax on the lightly engraved metal, and etching the engraved lines not protected by this resist. The idea of making a plate solely by etching may be as late as 1600. The process as eventually established used a relatively soft compound, the etching-ground, which was dabbed out thinly on the heated plate. This surface was then blackened, and the etcher drew on it lightly with a steel point, the etching-needle, to expose the metal below. Etching with acid, generally dilute nitric, removed metal from the exposed lines, and when the required depth had been obtained anywhere it was protected by varnishing. After the first etching the ground could be relaid to add further work; or additions could be made with dry-point or burin. There were no important developments in the process, apart from the transition from etching after engraving to pure etching. The former was practised from about 1500 onwards by German etchers, including Dürer, and their successors in Austria, Italy, and the Netherlands, while between 1600 and 1730 the great development of pure etching is associated particularly with the Netherlands and above all with Rembrandt.

Finally, in the mezzotint process we have an identifiable invention. Ludwig von Siegen, born in 1609, devised an intaglio plate covered with a fine pattern of indentations, which would pick up enough ink to print almost black, except where scraped or burnished away to give lighter tones or white. How he prepared his indented background is unknown: other early mezzotinters—including a notable amateur, Prince Rupert—used a knurled wheel, the 'engine' or 'roulette', but the tool eventually standardized, the 'rocker', was developed well before the end of the seventeenth century. It was a hardened-steel curved head, bearing parallel serrated ridges, mounted on a short handle. Pressed down on a copper plate and rocked, it left a small area patterned with shallow furrows, each with a burr at either side. By repeating this pattern at angles of 90° and 45° to the first one, the engraver broke up the ground into a grained texture, which could be varied in quality by having rockers of different fineness and by altering the angles of rocking. Only two other tools were needed: the scraper, used to remove the burrs where a slightly lighter tone was needed, and the burnisher, with which the indentations could be polished away to give light tones and white.

There were no significant developments of the mezzotint process itself before 1730; but at that date J. C. Le Blon was experimenting in the three-colour process using mezzotint plates, an idea whose later developments were to be extensive.

All four processes of intaglio printing had certain common features: the metal used for plates, the ink, and the method of impression. The metal was commonly copper, which was soft enough to engrave and hammer up for correction easily and could be etched readily, but iron, pewter, silver, and zinc were all sometimes used. The ink was an oil-based one similar to letterpress printing-ink, but rather thinner to ensure that it ran into the finest grooves. The method of printing at first was to ink the plate, wipe the surface, place a double thickness of damped paper on it, and rub down with a rounded tool. Later—probably about 1500—the double-roller press came into use. This simple device is in principle a mangle (figure 253). The early wooden ones had two rollers mounted about 1½ in apart between strong wooden cheeks, on either side of which was a table level with the top of the lower roller. The neck of the upper roller projected beyond the cheek, and had spokes inserted into it. In use, a large wooden board was placed on one side table; the engraved plate was placed to a previously marked position on it, after being inked and wiped; the damped paper, backing sheet, and some soft packing were put on top; and the whole board was slid between the rollers and driven through by the powerful leverage exercised on the spokes of the top roller. Neither the rolling-press nor the printing method altered significantly during our period; iron gradually replaced wood for the spokes, necks, and bearings of the rollers, but the all-metal press is a later development.

Special uses of intaglio techniques. Of the four techniques described, dry-point and mezzotint, because of the short life of the plates, were used mainly by artists for limited reproduction of their works, though the special usefulness of mezzotint for reproducing paintings led it to be used occasionally for illustrating small editions. Both etching and engraving, however, could be used for comparatively large numbers of prints, particularly of simple line subjects. It was not long, therefore, before intaglio plates were used to illustrate books printed from type, particularly where fine lines were needed, as in maps, geometrical diagrams, and mechanical or architectural drawings. Normally they were printed on separate leaves—hence the term 'plates' for illustrations not incorporated in the text—and sometimes by a different establishment; but during the sixteenth century it became common for large printing-offices to have their own rolling-presses and to print intaglio work registered with the text. In the seventeenth century the engraved title-page became fashionable, and in expensive works engraved diagrams, chapter-heads, and tail pieces might be used throughout. Above all, engraved plates lent themselves well to the reproduction of maps. The first two engraved maps are in two editions of Ptolemy (Bologna, 1477, and Rome, 1478).

One other important use for engraving was found, in the reproduction of music. The use of wooden blocks and music type has already been noted: the former were slow to produce, easily damaged, and difficult to repair, while music type is so complex that its use requires specially skilled compositors. Both type and wooden blocks remained in use throughout our period when it was required to combine music and text in one printing, but, once the technique of music engraving was established, its superior appearance and economy soon made it the standard method.

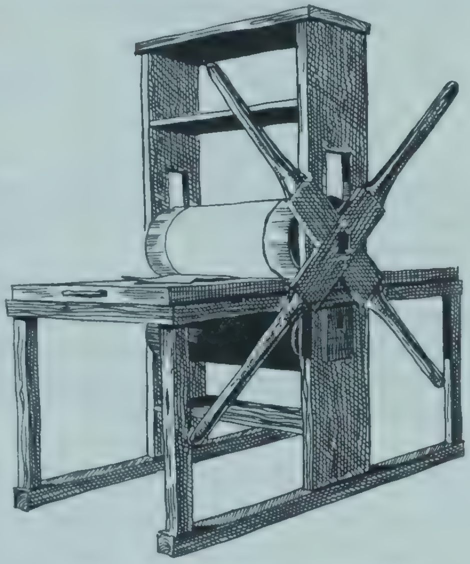

FIGURE 253—*A primitive rolling-press.*

It is curious that the first engraved music-printing to survive is a book published in 1586 by Simone Verovio of Rome and engraved by Martin van Buyten, a Dutchman. It was probably not their first production; and though there are earlier claimants, Verovio almost certainly first developed a commercial process. Others adopted it at once; the Dutch at this time had a lead in the intaglio techniques, and travelling engravers helped to spread this new application of their art. It had reached England by 1598, when Thomas Morley secured a patent, and during the seventeenth century its use extended throughout Europe until by 1730 music printed from type had become unusual.

The process at first was to engrave notes, tails, lines, and all markings on a plate of copper, though pewter may have been used in the seventeenth century for some ephemeral work. Soon after 1700 the Dutch had apparently mastered the annealing of large copper plates well enough to allow the notes to be punched in, and about 1720 this method reached England, where it was found equally satisfactory using pewter, the metal eventually standardized for music plates. With a scoring-tool to rule the staves, and a set of 50 or 60 punches to produce the main notes, tails, and other markings, the music printer had, by 1730, a process which was not to be improved in speed for nearly a century and has not yet been equalled in elegance.

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The literature on the history of printing is extensive, but the historical value of much of it is negligible. Even in the last ten years books have been published reasserting legends that have long since been disproved, and repeating from previous authors information that is demonstrably untrue.

The following list includes only a few of the books which have been of direct value in preparing this article, selected as giving a reliable general review of the subject or as including useful bibliographies, references to documentary sources, or accounts of original research. I am particularly grateful to the Librarian of the St Bride Technical Library, London, for directing me to some of the sources used.

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A NOTE ON TECHNICAL ADVANCES IN THE MANUFACTURE OF PAPER

BEFORE THE NINETEENTH CENTURY

JOHN OVERTON

THE development of the Fourdrinier machine at the beginning of the nineteenth century made it possible for paper to be manufactured on continuous reels. Until then paper was made by hand, sheet by sheet, but the processes involved did undergo some rationalization and changes in technique, all of which anticipated and contributed to the great technical advances that took place subsequently. These advances enabled paper to be manufactured at a greater speed and with greater consistency, and the use of various chemicals made it possible to produce special papers for particular purposes. By these innovations, however, the character of the resulting sheet was considerably altered.

Basically, the paper-making process remains unchanged whether the paper is made by hand or by machine. Raw material consisting of linen, cotton, straw, wood, or other material is reduced to a pulp by a beating process and mixed with water which serves as the carrier of the fibres. When the pulp is spread out over a wire mesh the water drains off leaving the fibres to form the paper. The mesh is given a shake to felt the fibres together. The paper is then dried, and possibly smoothed to give a satisfactory sheet (figure 254).

One of the earliest major technical advances occurred in the beating process. This was the introduction of the stamping-mill, very soon after paper-making was first introduced into Europe; it is thought to have originated at Xativa in Spain about A.D. 1150, and consisted essentially of an elaborate wooden mortar and pestle. Usually the mills were arranged in batches of three or four, although larger assemblies are known to have existed. The pestle was operated by one extremity of a wooden arm, pivoted at the middle (figure 255) rather like a see-saw, whose other extremity was depressed by tappets on a shaft rotated by hand, or later by water- or wind-power. To make the process more effective spiked stampers were made which cut the rags into smaller pieces. The rags were then subjected to a beating by stampers without spikes, which frayed them, as before, the object always being to separate the material into the fibres of which it was composed. During the first stages of the stamping, water was pumped into the stamping-troughs and drained off again, to wash the material being beaten; but the flow of water was usually discontinued during the later stages of the operation.

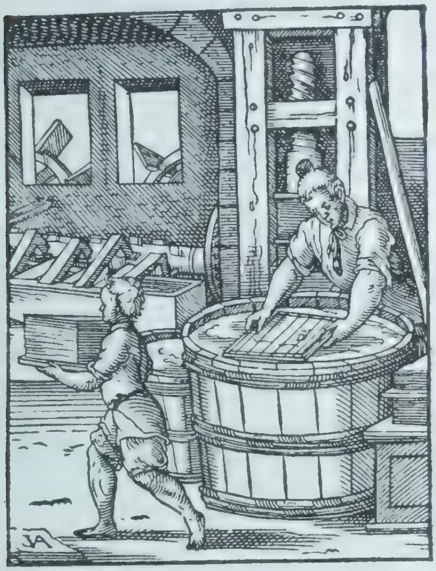
FIGURE 254—*The first illustration of a paper-maker at work.* (At rear) *Water-driven stamp-mill;* (centre) *press for squeezing sheets;* (foreground) *vat-man using the mould, while his boy carries away finished sheets. 1568.*

This process underwent a further change with the invention of the 'Hollander' by the Dutch in the late seventeenth century (figure 256). This machine stamped or, as it was now termed, 'beat' the rags in an oval-shaped vessel, containing a cylinder on which knives were mounted. This machine was constructed in such a way that the mixture it contained was circulated by the rotating cylinder, so that all parts of the mixture passed underneath the knives. The Hollander itself was subjected to many refinements. One of these machines produced more pulp in one day than did eight stampers in a week.

The linen and cotton rags used to make the pulp were usually thrown into a heap and allowed to disintegrate by fermentation, sometimes after the materials in the bundles had been sorted, in which case the different types were beaten separately and mixed as required. This process was occasionally helped by the addition of lime. Later, the lengthy and wasteful fermentation of the rags was given up, chiefly because it was rendered superfluous by improved beating methods and by the practice of boiling the materials. The yellowish tint of early papers can often be ascribed to it.

When the pulp was ready for the paper-maker it had to be transported to the vat. At first the pulp was carried in buckets, but, by simply rearranging the apparatus, the vat became gravity-fed. Eventually, when the time factor became of importance and the paper had to be made more quickly, the vat had a heater placed against it. This warmed the pulp and increased the rate of evaporation. It could not, however, be made too hot, otherwise the evaporation became too fast and the resulting stresses in the paper-pulp produced a bad sheet, usually one that would not lie flat and on which it was therefore difficult to print. The vat was further improved by the addition of a rest for the mould, so that surplus water could drain off before the sheet was removed by the coucher. The shape of the pole ('hog') used for stirring the pulp in the vat gradually developed to make the stirring more complete, while later still (*c* 1800) an agitator was incorporated in the vat.

The paper-maker or vat-man dipped a mould into the vat. This mould consisted of a wooden frame to which were fastened a number of tightly strained parallel wires (laid-wires) running the length of the frame. On top of this arrangement was a separate frame, the 'deckle', which formed the boundary of the sheet (figure 257). This boundary was not as a rule clean-cut, for the pulp tended to penetrate between the deckle and the wire frame. The frame was traversed from side to side by a number of ribs, and it was to these and to the ends that the wires were fastened. The wires used for fastening the laid-wires to the ribs were called chain-wires and produced the chain-lines in the sheet. This type of mould was improved by the substitution of wire supports for the ribs to which the laid-wires were fastened. This gave a more even sheet of paper. The difference can be detected by the heaviness of the shadow on either side of the chain-line marks on the paper. The heavier shadow denotes a mould of the early type, for the extra width of the wooden ribs tended to retard the heavy drainage of water on either side of the chain-wires, so that more pulp collected there. The number of laid-wires to the inch was gradually increased. Some of the early moulds, particularly the oriental moulds made of bamboo, were very coarse. The paper on which the Gutenberg Bible (p 386) was printed had 28 laid-lines to the inch.

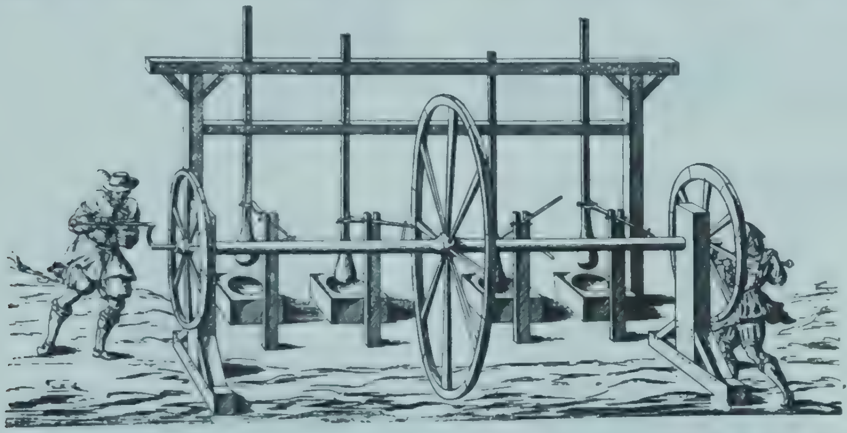

FIGURE 255—*Manually worked stamp-mill of a simple kind which could be used for beating rags to make paper. 1579.*

The most easily recognizable distinguishing mark on paper, the watermark, first appeared in paper made in Italy about 1285, in the shape of a cross. The earliest marks were usually very simple in design, but during the fifteenth century they became more and more complicated. They were all made by means of wire bent into the required shapes and then sewn to the mould with finer wire. This practice, and the whole construction of the mould, depended on the development of wire-drawing techniques. Watermarks served to identify the products of individual mills, and often had esoteric significance as well. Some of them, such as the cap and bells of a jester, were the origin of terms now used to describe various sizes of paper.

The coucher, having deposited the sheet of paper from the mould on a felt cloth, placed another felt over it and upon this another sheet of paper and so on until he had an interleaved pile containing 144 sheets of paper, called a post. This was squeezed in a wooden screw-press to remove surplus water. At first the sheets of paper were hung for drying immediately after pressing; during the sixteenth century, however, the felts, after pressing, were removed from between the sheets and the latter were pressed again, and then again, until the surface of the sheet was of the required finish. This process was called 'sweating'. Another way of giving a higher finish to the paper was to use a smooth stone which was rubbed over the completed sheet. The stone was superseded at the beginning of the seventeenth century by the glazing-hammer; the sheet was moved about under the hammer until its entire surface had been beaten. Wooden glazing-

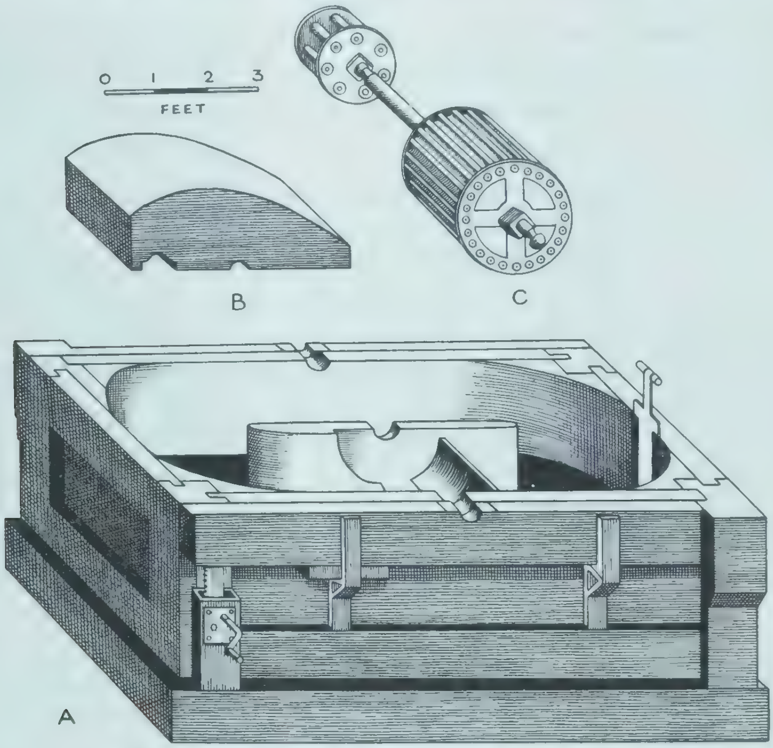

FIGURE 256—*The Hollander.* A, *wooden tub containing water and material to be disintegrated, which flows round the central partition.* B, *cover over cylinder.* C, *cylinder of knives, rotated by a water-wheel so that the blades sweep close to the curved flange in the tub. The clearance is adjusted by the rack which raises and lowers the near bearing for the cylinder. On right of the tub, paddle for running off the contents. The whole device is somewhat like a modern lawn-mower in operation.*

cylinders came into existence in the early eighteenth century, the sheet being passed between a pair of them under pressure.

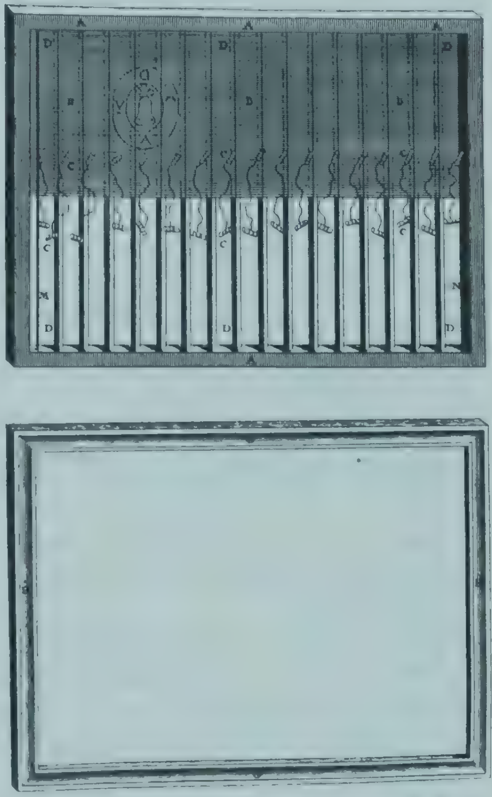

FIGURE 257—*Mould and deckle. The wires of the mould* (above) *are held down to the wooden ribs by wire passing round them and round nails driven into the sides of the ribs. Note the water-mark symbol wired in position. 1698.*

The paper was then hung in lofts to dry. It was hung in batches ('spurs') of four or five sheets together, because this was found to preserve their smoothness. The sheets were lifted by means of a T-shaped wooden implement and hung on ropes made of horse-hair or cow-hair, usually coated with beeswax. The ends of the ropes were fixed into spars of wood made to slide up and down vertical posts called tribbles, eight or nine of which filled a room. A wheeled table was used after a time to convey the sheets of paper. When the tribble-lines were full the spars were pushed up and retained by wooden pegs.

After the fifteenth century paper was often sized, particularly if it was to be used for writing. This was done by suspending the sheets from a piece of wood and lowering them into a container full of the sizing-material. After squeezing the surplus size out, the sheets were separated and allowed to dry. The material used for the sizing was usually the refuse from tan-yards called 'scrolls'.

The high-lights of the technical advances made in the early European manufacture of paper were: the use of the stamping-mill (1150); the invention of the watermark at Fabriano (near Ancona) about 1285; the use of wind or water as a source of power to drive various machines; the invention of the Hollander (1670); and the invention of the wove mould (1750).

Much inquiry was, however, directed to the use of materials other than rags for the making of paper. The search was intensified when the practice of papering walls for decoration was introduced about the middle of the seventeenth century. The patents registered to the end of that century dealing with various aspects of the paper industry do not appear to have passed beyond the beating stage. It is not until 1800 that the name of Matthias Koops appears, with a method of using straw for the making of paper and another of extracting the ink from printed paper, re-pulping it, and using it again. Koops's enterprise failed, but it anticipated the later transition to esparto and wood-pulp fibres. Two years before (1798) Nicolas-Louis Robert (1761–1828) obtained the first patent for a paper-making machine. His ideas, meeting with little encouragement in

France, were developed in England by Bryan Donkin (1768–1855) with the aid of capital provided by John Gamble and the Fourdrinier brothers, stationers in London. The 'Fourdrinier' machine thus evolved was rapidly improved upon during the succeeding thirty years, and is still in general use in the paper-making industry. Variations of it are employed for special purposes, such as making glazed paper.

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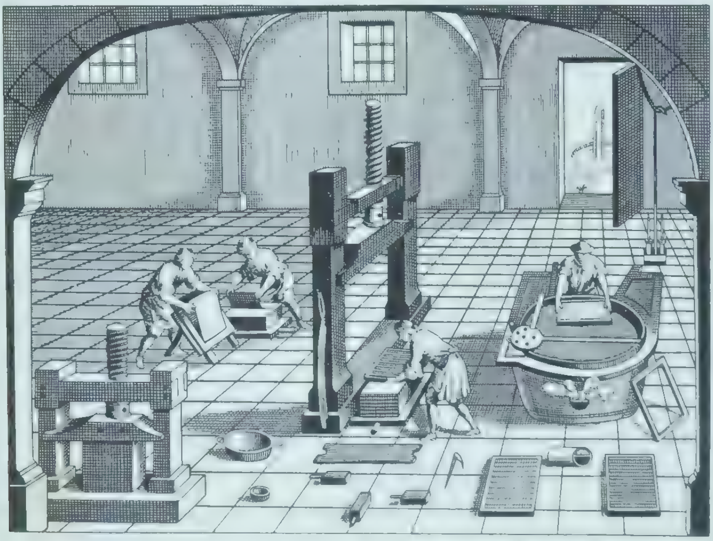

French papermakers of the eighteenth century at work in a factory.

16

BRIDGES

S. B. HAMILTON

I. EARLY BRIDGES

THERE are three main types of bridge. From ancient times trackways have been carried across deep gorges on the China–Burma border and similar places by ropes slung between opposite cliffs. The same device was used early in the thirteenth century, but with chains instead of ropes, when the St Gotthard route was made for pack-horse traffic across the Alps. The suspension bridge was, however, little used in western Europe until in the early nineteenth century it became technically and commercially practicable to forge strong links of wrought iron bars.

In the second type of bridge the arch is in principle an inverted chain (figure 274) with all its links compressed. This has been by far the commonest form of bridge-structure, the links being either wedge-shaped blocks of stone, or balks of timber strutting up a deck from a trestle (figures 266, 268).

The third type of bridge-structure is the beam, in which the top fibres are in compression and the bottom fibres in tension. The beam, however, can be made suitable for long spans only when it takes the form of an open-framed girder. Such girders were actually illustrated in the sixteenth century; Andrea Palladio in designing a truss (figure 265) clearly understood which members were in compression and which in tension, but he had no idea of the magnitude of the forces [1].

The arch was used in ancient Sumeria and Egypt, but for little except work underground (vol I, figures 295, 304). Its use as the main structural feature of monumental buildings and important bridges was first practised by the Romans. The army built wooden bridges on trestles (vol II, figure 467), but if the route remained as an important highway the trestles were in time replaced by great piers of masonry capable of withstanding flood and ice; later a series of masonry arches replaced the wooden decks. The piers were often built half as wide as the spaces left between them. The arch-rings were nearly always semicylinders of large stones so carefully dressed at their radial meeting-faces that little or no bedding mortar was needed. The whole width of an arch might not be completed in one operation; several rings were built successively side-by-side using the same centring.[1] The adjacent rings were commonly fastened together by iron cramps run in with lead. Some Roman bridges have lasted over 2000 years and still stand (vol II, figure 465); but many have fallen, or have been destroyed in the course of military operations.

The maintenance of roads and bridges was sadly neglected after the fall of the Roman Empire. Only strategic routes received the attention of the great rulers. In a few places civic pride or piety led to the building of a fine bridge at a dangerous and busy ford. According to one legend, medieval bridges were the special care of an order of Brothers of the Bridge (vol II, p 525), dedicated to the erection and maintenance of bridges; but this pleasing story finds little confirmation in contemporary sources [2]. The Pont d'Avignon (1177–85) (figure 258) had twenty-one elliptical arches, with a span of about a hundred feet and with the major axis vertical. The arches still standing may, however, date from a fourteenth-century reconstruction.

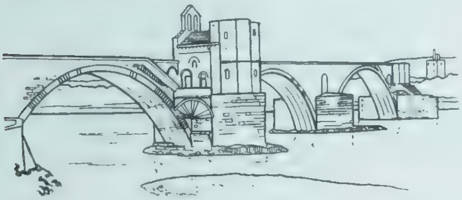

FIGURE 258—*The Pont d'Avignon. At the foot of one pier can be seen what may have been the springing of one of the original arches (1177–85).*

The Ponte Vecchio at Florence (1335–45) had three segmental arches, one of 95 ft in span and two of 85 ft, with a rise of rather less than one-sixth of the span; but most medieval bridges in Europe were built on the Roman model with semicircular arches. Occasionally in hilly country, where piers in a fast-running stream would have been difficult to construct and perhaps impossible to maintain, bridge-builders of the late Middle Ages and Renaissance constructed single segmental arches of span greater than any built by the Romans. Deep arches were sometimes built in several concentric rings, so that the first ring completed could relieve the centring of part at least of the weight of the next ring.

England, for a good reason, is peculiarly rich in medieval bridges. William the Conqueror, in rewarding his followers with grants of land, gave to each a number of small, scattered estates individually incapable of serving as a solid centre of resistance. To supervise his bailiffs every considerable landlord had to travel; bridges were built by local landowners, lay and ecclesiastical, by corporate boroughs, and by *ad hoc* trusts, the owners looking to tolls to repay the cost. In some places such as London and Bideford the bridge proved a lucrative investment. Most English bridges, being intended only for horse-traffic and pedestrians, were narrow, and many were steep. The individual arches were of no great span and, particularly if pointed at the crown, exerted but moderate thrust on their wide and massive piers. Usually only the facing-stones of the piers (and not always these) were of dressed masonry; the infilling was of rubble and lime mortar (figure 259).

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[1] Temporary wooden arch used to support the incomplete masonry arch.

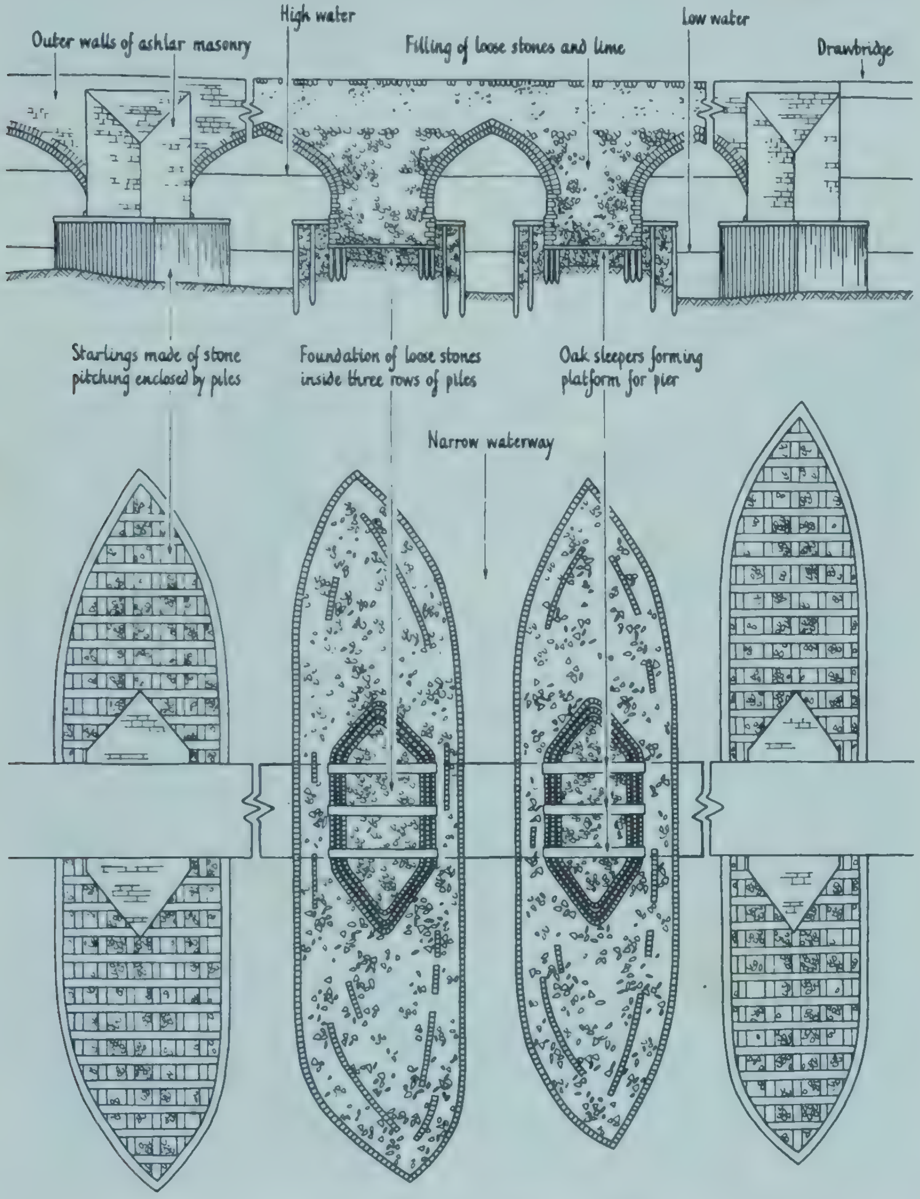
High water
Low water
Outer walls of ashlar masonry
Filling of loose stones and lime
Drawbridge
Starlings made of stone pitching enclosed by piles
Foundation of loose stones inside three rows of piles
Oak sleepers forming platform for pier
Narrow waterway

FIGURE 259—*Old London Bridge, after drawings made during its demolition, 1826–31.* (Above) *Elevation;* (below) *plan of the starlings.*

During the sixteenth and seventeenth centuries there were no drastic or fundamental changes either in the materials or in the form of bridge construction. The technique of bridge-building was still largely medieval, though improved tools and mechanical devices such as the crane allowed a reversion to the classical mode of building with large stones accurately dressed. A marked improvement in pile-drivers, pumps, and dredgers also made practicable the preparation in difficult places of sounder foundations than either Roman or medieval builders had been able to construct.

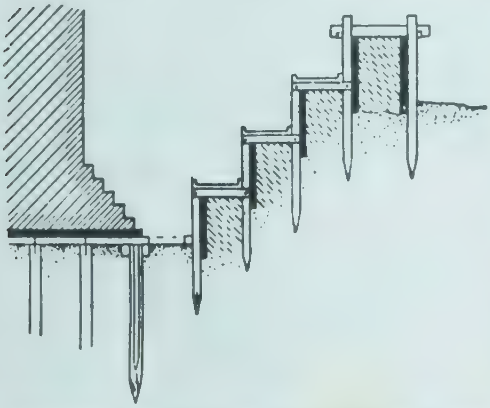

FIGURE 260—*Stepped coffer-dam used in constructing the Pont Neuf, Toulouse. The masonry of the pier, with piles beneath, is shown on the left.*

II. FOUNDATIONS

Many ancient and medieval buildings have either collapsed or required extensive restoration because their foundations have been compressed, or squeezed out, under their load. Failures of bridges have been even more numerous: the designer of a building had some choice of site and could usually avoid one which was always wet, but the bridge-builder had most often to construct his bridge where traffic had already converged towards an existing ford. He might have to contend with flood, ice, and the tendency of the river to scour its bed and shift its course.

The bridge-builder's first consideration was whether to lay his foundations in water or within a drained enclosure. If the bed were hard and the water shallow, as it frequently would be at a ford, he might decide to lay them in water. He had then to raise the river-bed in places up to at least low-water level, either by sinking loads of rubble or quarry-waste in wicker-work containers, or by disposing it within an enclosure, formed by a stockade of piles driven into the river-bed. Each island so formed provided a plinth upon which to raise a pier of masonry. Such artificial islands or 'starlings' obstructed the passage of the river and quickened its pace through the gaps, which often led to heavy scour. With every repair to the piers the free water-way tended to become still narrower.

Old London Bridge (figure 259), begun in 1176, so obstructed the flow of the Thames at a point where the spring tide rose and fell about 16 ft that at half-tide the water-levels above and below the bridge sometimes differed by several feet, making passage by river-traffic impossible. In the sixteenth century matters were made worse by the installation of water-wheels and pumps under some of the arches. When one pier was demolished in the eighteenth century to make a double-width channel for shipping, the race through the widened gap became

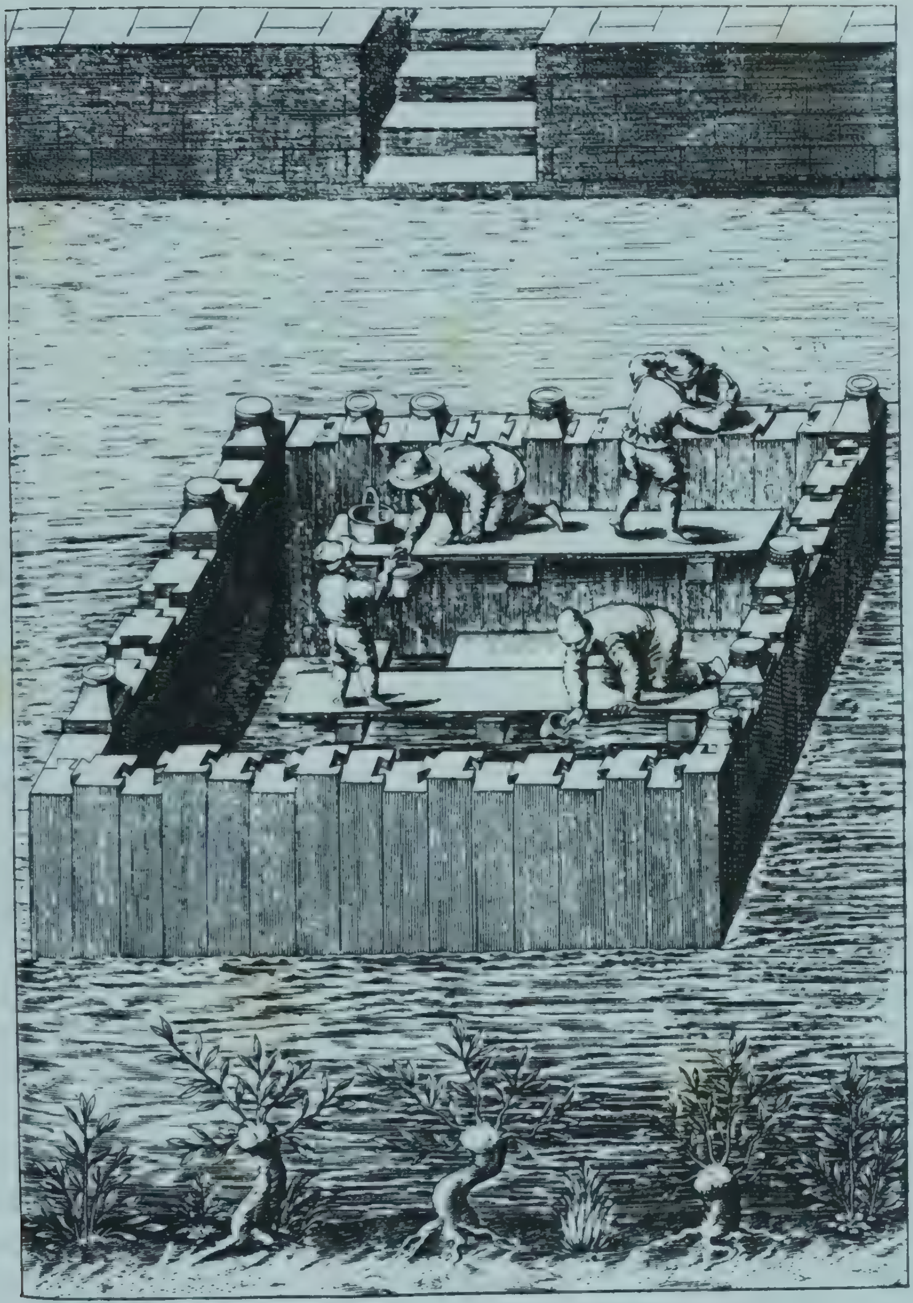

FIGURE 261—*A coffer-dam made of interlocking piles. From Ramelli, 1588.*

so fierce that a deep groove was cut in the river-bed, threatening to undermine the two nearest piers. Disaster was averted only by tipping in large quantities of stone with all haste, so forming a submerged weir across the gap.

The alternative to building on artificial islands was to sink the pier-foundations into the ground below the river-bed. To do this the river had to be diverted or part of its bed enclosed within a water-tight coffer-dam, from which water was removed by pumping. The construction of a coffer-dam was no light task. If the water was deep the dam had to be built in steps (figure 260) [3]. The outermost two rows of posts were driven in, horizontal beams were fixed to them and strutted apart, and the space of about 3 ft between the rows was cleared of earth, mud, or gravel as far down as this could be done with a long-handled scoop. The cleared space was then filled with puddled clay up to the high-water level if possible, and at least somewhat above low-water level. The material for puddling had to be most carefully chosen. A soft, sticky clay alone would work into mud; some sand or gravel had to be present or mixed with it to make a plastic mass, which could be worked like putty and well rammed in to form a water-tight barrier. When the dam was complete it was possible to pump out the water and dig down to a firm bottom for the bridge-foundation. Driving large numbers of piles was laborious and expensive; so was pumping great quantities of water. Both required gruelling, repetitive labour by relays of men over long periods. The closer the piles fitted together the better would a coffer-dam keep out water. Interlocking, or dove-tailed, piles were tried. Ramelli's illustration of 1588 (figure 261) [4] might be distrusted as a flight of fancy if it were not known that Captain John Perry (1715) used an almost identical form in his work to stop the Dagenham breach in the embankment of the Thames; he had previously seen it used in the royal dockyards [5]. Interlocking piles, however, were seldom used until the twentieth century, when they were made of steel and driven by steam hammers.

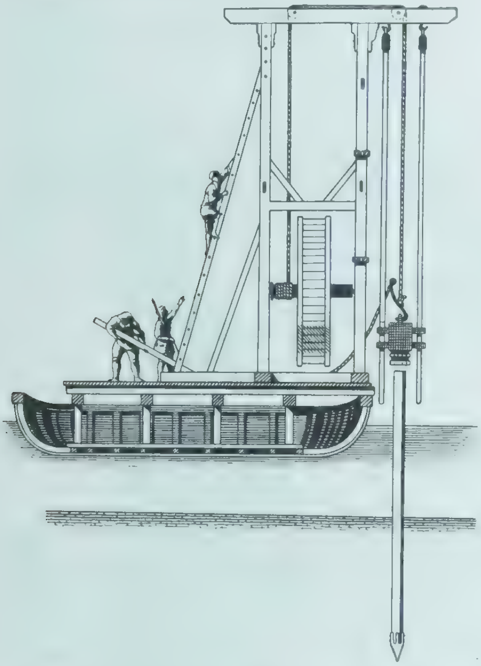

FIGURE 262—*Pile-driver mounted on a barge. The hammer is raised by the treadmill, seen end-on. When it is high enough to tighten the rope attached to the end of the shank of the hook, the hook is withdrawn from the eye in the hammer, so that it falls upon the pile. 1750.*

B. F. de Belidor (1693–1761), in his *Architecture hydraulique* (1737), showed several ways of driving piles. In one case (figure 262) the pile-driving frame is mounted on a barge, the hammer being raised by men working a treadmill and released by an automatic trip-gear. Similar machines are shown in sixteenth-century books and manuscripts (figure 263) [6]. After the fall of the hammer the rope had to be unwound from the drum and the process repeated hour after hour, day after day. To keep the coffer-dam clear of water some kind of pumping or baling device was needed. In the eighteenth century this would usually be an endless chain, either linking plates that worked in an inclined trough, or carrying cups or balls that nearly filled the bore of a vertical pipe. Sometimes the Archimedean screw was used. Occasionally the current of the river, with half its bed obstructed by coffer-dams, was strong enough to operate a water-wheel to work the pumps.

Once the coffer-dam was made and the water pumped out, mud and loose silt could be removed until the solid bed was exposed. If this were of gravel or stiff clay it would be levelled and a deck of thick planks or balks of timber laid first one way, then across, with a third layer in the same direction as the first. Sometimes a bed of concrete was laid instead of a platform grillage of planks; on this or the grillage the masonry pier could be built direct. It might happen, however, that no firm bottom had been reached by the time the digging was as deep as the engineer cared to trust his coffer-dam. Then piles were driven in the bottom and sawn off level, to be capped with timber or concrete. The Pont Notre-Dame in Paris, which was built of stone in 1507 to replace a medieval wooden bridge, was founded on concrete on piles. The superstructure was rebuilt in 1853, but the foundations were still sound enough to be embodied in the new work. In 1913–14, however, all except the two shore spans were replaced by a steel arch. The piers in mid-stream were demolished, and the two that remain were widened and strengthened.

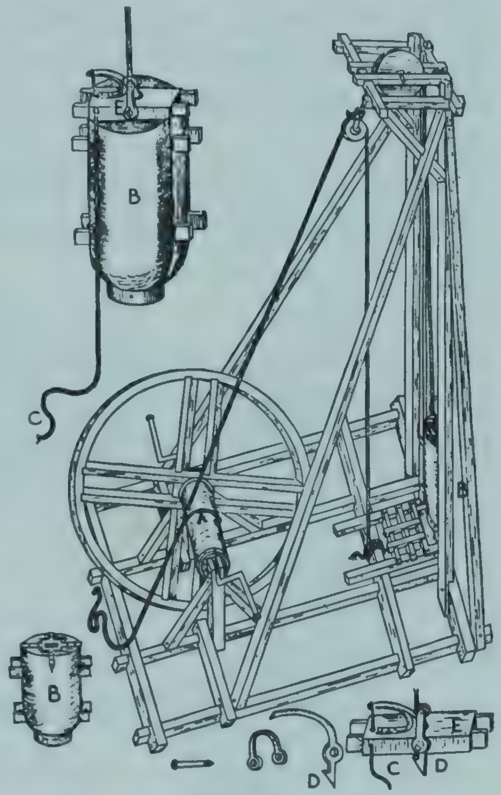

FIGURE 263—*Sixteenth-century pile-driver. The heavy weight* B, *descending in vertical guides, is wound up by the windlass* A, *turned by two cranks with the aid of a fly-wheel. When fully raised, the weight is released by pulling the cord* C. *This, acting against a spring, unlatches the catch* D *from the recess in the weight* (see details) *so that the latter is detached from the piece* E *and falls upon the pile.* E *is then lowered, attached once more to the weight, and the cycle repeated.*

The foundations of the celebrated Pont Neuf in Paris (1578–1607) were also dug inside a coffer-dam. They were laid 10 ft above the bed-rock, but the difficulty of sinking that extra distance would have been enormous. It proved unfortunate, however, that no bearing-piles were driven down to the rock, for besides suffering settlement two piers were partly undermined by scour before the superstructure was finished. Sheet-piles had to be driven round the upstream toes of the piers and strapped back to the repaired masonry. Settlements continued, yet even in 1848 only the superstructure was completely replaced.

The coffer-dam for the foundations of the Santa Trinità bridge at Florence (1567), or at least its lowest stage, consisted of two walls, 7 ft thick and 90 ft apart. These were of concrete laid between rows of sheet-piles driven right across the river-bed, and were connected by cross-walls to form compartments for the individual piers. They were later left level with the river-bed as a protection against scour. The ground was dug out to 13 ft below the river-bed; piles were driven in the bottom, cut off level, and capped by large foundation-stones.

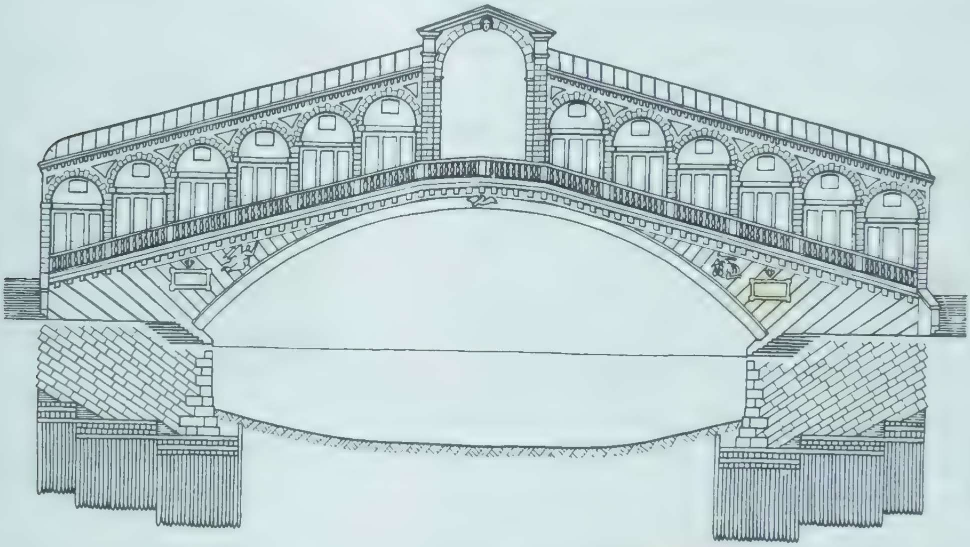

FIGURE 264—*The Rialto bridge, Venice.*

Somewhat unusual precautions were taken to ensure the stability of the Rialto bridge at Venice (1588–92), a single-arch span of 88 ft. The subsoil was alluvium to a considerable depth, and it was essential to safeguard the foundations of adjoining buildings. The designer, Antonio da Ponte, therefore decided to step the foundations (figure 264). Six thousand piles, each about 6 inches in diameter and 11 ft long, were driven in tight clusters beneath each abutment. This would not now be considered the best way to use piles, since the whole assembly could move as a solid block: fewer, longer piles more widely spaced would have spread the load better. Yet the foundations have not moved. On them the masonry was laid in inclined courses.

The Pont Royal in Paris (1685) was designed by J. H. Mansard (p 254), and supervised by Jacques (IV) Gabriel.[1] An elaborate specification was drawn up for the foundations. The coffer-dams were to be 9 ft thick of puddled clay between a double sheathing of timbers, and the ground was to be excavated to a depth of 15 ft below low water. Timber bearing-piles 10–12 inches in diameter were to be driven at 18-in centres each way over the whole base; the pile-heads were to be cut off level; and a timber platform was to be laid on them to carry the masonry. How much of the foundation-work, if any, was done according to this specification is not known. Until modern methods of site-investigation were developed—from about 1920—elaborate specifications of foundation-work expressed a hope rather than a promise. According to one account, trouble at the Pont Royal began with the first pier on the Tuileries side, and as a result a different procedure for building it was adopted [7]. The site was dredged level, and a great box or caisson floated over it and sunk there, presumably with several courses of masonry already laid inside. For the next stage the caisson served as a coffer-dam. The mortar used in laying the masonry contained pozzolana (vol II, p 407), an Italian volcanic earth forming, when mixed with lime and water, a natural cement capable of setting under water.

If this account could be believed, then the Pont Royal would provide the first instance of the use of caissons in bridge-building, of dredging to provide a foundation, and of the use of pozzolana cement in France. There is, however, reason to regard it as inaccurate [8], and if it be so the first use of caissons in the manner described is correctly attributed to the Swiss architect Charles Dangeau de Labelye (1705–? 1781). Belidor gives good illustrations of the process of dredging at this period [9].

The practice of dredging for bridge-foundations and the use of the caisson were brought to England by de Labelye when in 1738 he was appointed to build a bridge over the Thames at Westminster. The bottom of each caisson was a stout wooden platform 80 ft by 30 ft in plan. The side walls were 16 ft deep, fastened to the base-platform by wedges so arranged that sides and bottom made a watertight caisson, which could be flooded through sluices or pumped dry as required. The platform for each pier remained part of the permanent structure. On withdrawal of the wedges the sides could be released for use in another caisson. There were twelve piers, two abutments, and thirteen arch-spans. The area

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[1] The Gabriels were a celebrated family of French architects. Jacques (V) (1667–1742) was principal architect to the king, and Jacques (VI) (1698–1782) designed many of the buildings flanking the Place de la Concorde.

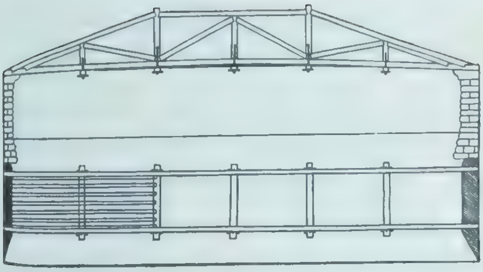

FIGURE 265—*Truss-girder bridge designed by Palladio. 1570.*

within which each caisson was to be sunk was first surrounded by a wall of sheet-piling, within which the bottom was dredged and left level at a depth of 6 ft below the river bed for an area of 90 ft by 40 ft between toes of slopes. No piles were driven below the site of any pier. The caisson, loaded with two courses of masonry, was sunk in position, then refloated and loaded with a third course, and the sides were strutted from it while the bed received a final trim. The caisson was then sunk in its final position, the top of the masonry being about 2 ft above low water at spring tides. At high tide the caisson was submerged. Pumping began as soon as the top of the caisson appeared above water on the ebb tide, and the building of the pier was recommenced as soon as the masonry was exposed. Even when the sides of the caisson were removed, the masonry piers obstructed one-fifth of the river-passage. It is therefore not surprising that the gravel bed scoured in places, or that one pier settled unevenly before the bridge was completed. That pier and the two arch-spans to which it gave support had to be demolished and rebuilt, a misfortune that retarded the completion of the bridge by several years. Other settlements occurred, and when, about 1840, the roadway was widened a permanent coffer-dam of sheet-piles was left surrounding the lengthened

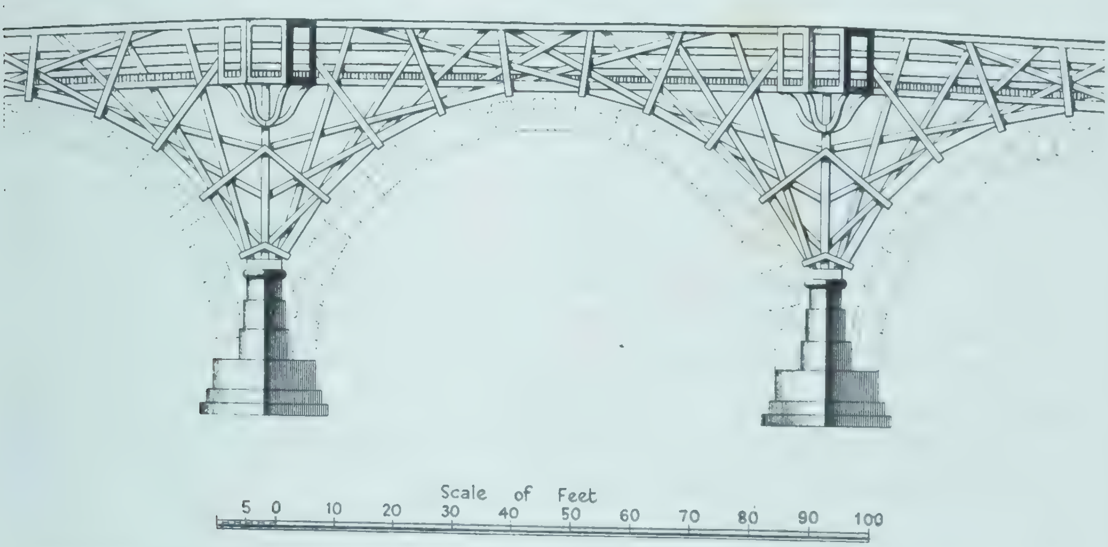

FIGURE 266—*The stone piers of Westminster bridge and the wooden superstructure originally proposed. The masonry arches actually built are shown by dotted lines.*

piers. The gap between this piling and the masonry was filled with concrete and capped with slabs of stone [10].

III. SUPERSTRUCTURE

Wood has probably been more widely used than any other material for bridge-building, and still finds much employment in temporary bridges, especially in oversea dependencies. Like its later competitor, steel, timber is strong both in tension and compression, but before the introduction of the toothed-washer type of connector in the twentieth century the making of a neat, economical joint to transmit a heavy pull from one timber-member to another was difficult. The carpenter, therefore, used most of his material in compression or bending, and tried to arrange that only light loads should be transmitted by joints which put members in tension.

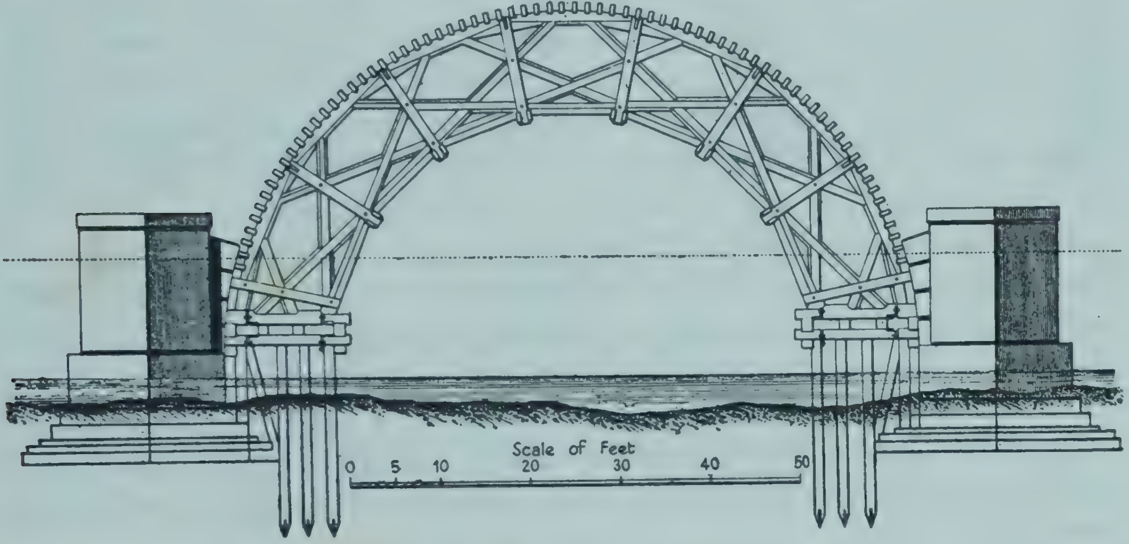

FIGURE 267—*The timber centring for the central arch of Westminster bridge; span 76 ft. 1739.*

As early as the sixteenth century Andrea Palladio (1518–80) illustrated a true truss-girder bridge of 100 ft span (figure 265) [1]; but this construction was not widely favoured until, nearly three centuries later, it was developed by American engineers.

As late as the 1730s it was proposed to build Westminster bridge with a timber superstructure as shown in figure 266, the framework virtually forming an arch. The centring on which the masonry ring was laid was also an arch (figure 267). The remarkable bridge over the Rhine at Schaffhausen below Lake Constance (figure 268), erected in 1757 by the Swiss engineer Hans Ulrich Grubenmann,

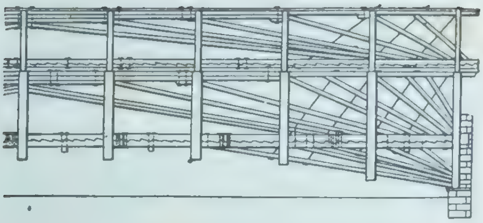

Figure 268—*Grubenmann's bridge over the Rhine at Schaffhausen (half of one span).*

was a framework of struts forming a rather complex arch combined near the abutments with a lattice-girder of which the members in tension were iron rods. The bridge was in two spans of 172 and 193 ft. It was roofed and boarded in to protect it from the weather. Grubenmann would have preferred to omit the intermediate pier and throw the two spans into one. Thomas Telford expressed the opinion that he could safely have done so, but the owners were more cautious. Even as constructed the bridge was reported to be very flexible even under pedestrian traffic. How long it might have lasted is uncertain, for it was destroyed by a retreating army forty-two years later. Grubenmann's even more spectacular bridge over the Limmat at Wettingen near Zürich, having a single span of 390 ft and a rise of 43 ft, suffered the same fate (figure 269).

The important bridges during our period were of the masonry-arch type. They differed from most medieval arch-bridges in that they tended to be built with large stones finely worked, as was ancient Roman masonry. The joints between the stones, particularly the voussoirs[1] of the arch, were close. Longer spans with smaller rises than in older bridges were made practicable by the wider use of flattish segmental or elliptical arches, and by a progressive decrease in the thickness of the arch at the crown. The width of the piers between spans was also reduced.

The Ponte Vecchio, or Bridge of the Goldsmiths, over the Arno at Florence was rebuilt in 1345 to an advanced design by Taddeo Gaddi (1300?–66). It was one of the first bridges in which a shallow segmental profile was employed. There were three spans of from 85 ft to 94 ft 6 in; the rise was from 12 ft 10 in to 15 ft, or between one-sixth and one-seventh of the span.[2] The pier-thickness was 20 ft 4 in, between one-quarter and one-fifth of the span. Neither of these ratios was often so low until Jean Rodolphe Perronet (1708–94) and his engineers of the Ponts et Chaussées systematically reduced them in the latter half of the

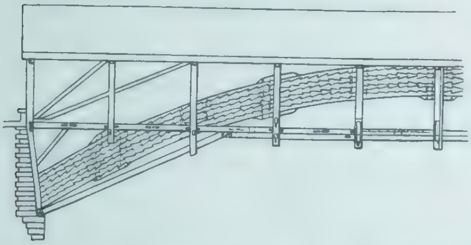

Figure 269—*Grubenmann's bridge over the Limmat (half of one span).*

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[1] The wedge-shaped stones forming the ring of the arch.

[2] The dimensions of bridges, unless one knows who measured them, should be accepted with caution; they are copied by one author from another. The dimensions of the Ponte Vecchio given above are from Edward Cresy's *Encyclopaedia of Civil Engineering* (London, 1847).

eighteenth century. The keystone was only 3 ft 3 in deep, or one twenty-ninth of the span, below which even Perronet would hardly have favoured a reduction. The Ponte Vecchio was, however, an exceptional bridge.

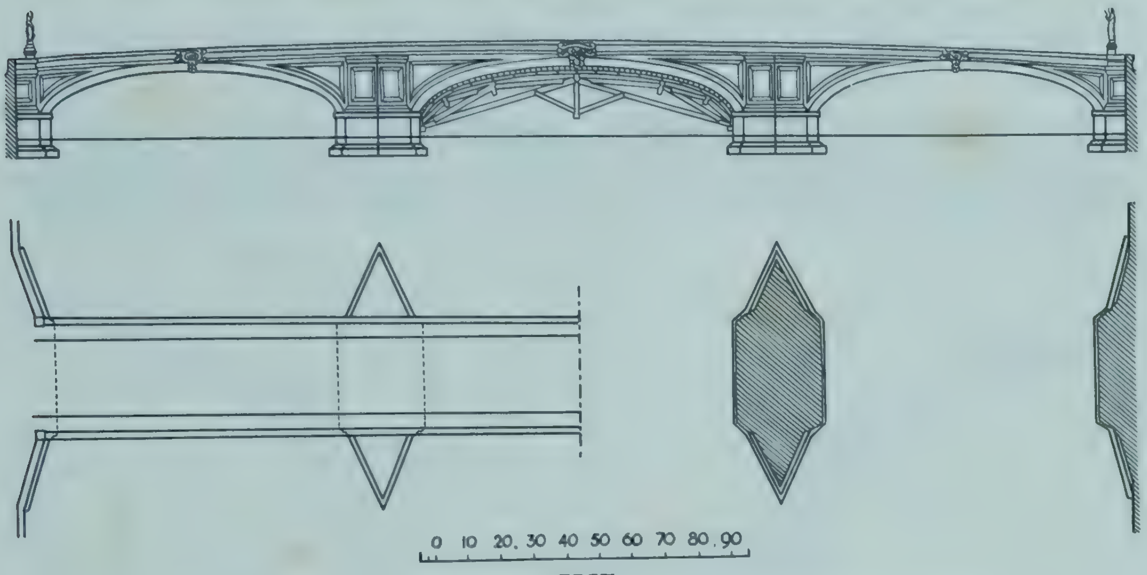

FIGURE 270—*The Santa Trinità bridge, Florence.* (Above) *Elevation;* (below) *plan.*

The usual proportions recommended were as follows:

Span	*Rise*	*Thickness at crown*	*Width of pier*
1	$\frac{1}{6}$–$\frac{1}{3}$ according to relative levels of road and river	$\frac{1}{12}$ (Alberti) $\frac{1}{15}$ (Palladio) $\frac{1}{17}$ (Serlio) $\frac{1}{24}$ (Perronet)	$\frac{1}{4}$–$\frac{1}{6}$

Henri Gautier (1660–1737) realized that bridge-piers were made far larger than was required for the support of their vertical loads, but neither he nor his successors cared to risk making them thinner. It was Perronet half a century later who actually reduced pier-thickness to one-tenth of the span. The end-abutments, and in a long viaduct an abutment-pier at intervals of every five or six spans, were built stout enough to take the thrust. The spans between two abutment-piers were all centred and built simultaneously, the intermediate piers being regarded as columns above which the thrusts balanced one another.

The three arches of the Santa Trinità bridge at Florence (figure 270) were of 87, 96, and 86 ft span. The design was in several respects remarkable. When the bridge was built in 1567 the semicircular arch was still usual, with the segmental arch as an alternative, but, to avoid steep approaches, the designer, Bartolomeo Ammannati (1511–92), gave each arch a rise of only one-seventh of the span, and adopted an unusual profile.

Settlements of the original centring, however, and later of the bridge, made it impossible to tell for certain by later measurements whether the original form was parabolic, elliptical, or multi-centred, or followed an artist's free-hand curve. The curve, moreover, was broken at the crown, where the halves intersected at an obtuse angle, giving a slightly pointed profile. The existing bridge is a reconstruction in facsimile, the original having been destroyed by the retreating Germans in the 1939–45 war.

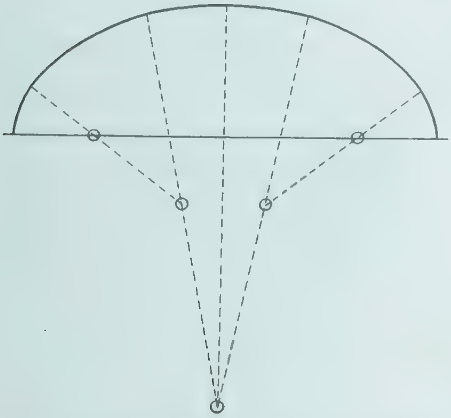

FIGURE 271—*Diagram showing the construction of a 'basket-handled' arch by means of arcs of circles struck from five centres. The result approximates closely to a semi-ellipse.*

The curvature of a true elliptical arch would vary continuously, and no two adjacent voussoirs could be cut to quite the same radius. To avoid this difficulty, the French engineers came to favour a false-elliptical, or 'basket-handled' form in which the radius of curvature varied discontinuously (figure 271).

The bell-mouthing of the openings of arches was a marked feature of later French practice. It was introduced deliberately in the upstream face of the Pont Neuf at Toulouse in 1542, and in both faces of the Pont Henri IV at Châtellerault, Vienne, in 1564. In the second of these bridges the faces of the arches sprang from near the points of the triangular cut-waters, the span of the elliptical arches being increased by about 6 ft while the rise remained constant (figure 272).

A curious feature of certain medieval and later bridges was their secondary use as a site for shops and houses. London Bridge (1209), the Ponte Vecchio at Florence (1367), the Pont Notre-Dame in Paris (1507), and the Rialto bridge at Venice (*c* 1590) were all so used. To build a bridge to provide a house with a foundation must be the most extravagant method possible! The piers of London Bridge were large; between tides they obstructed about half the width of the river, which at that point was rather more than 900 ft. The starlings (p 420), moreover, were much larger and at low tide obstructed about half the remaining width. They also extended up and down stream far beyond the sides of the bridge, leaving ample room for props to carry the houses. The city was con-

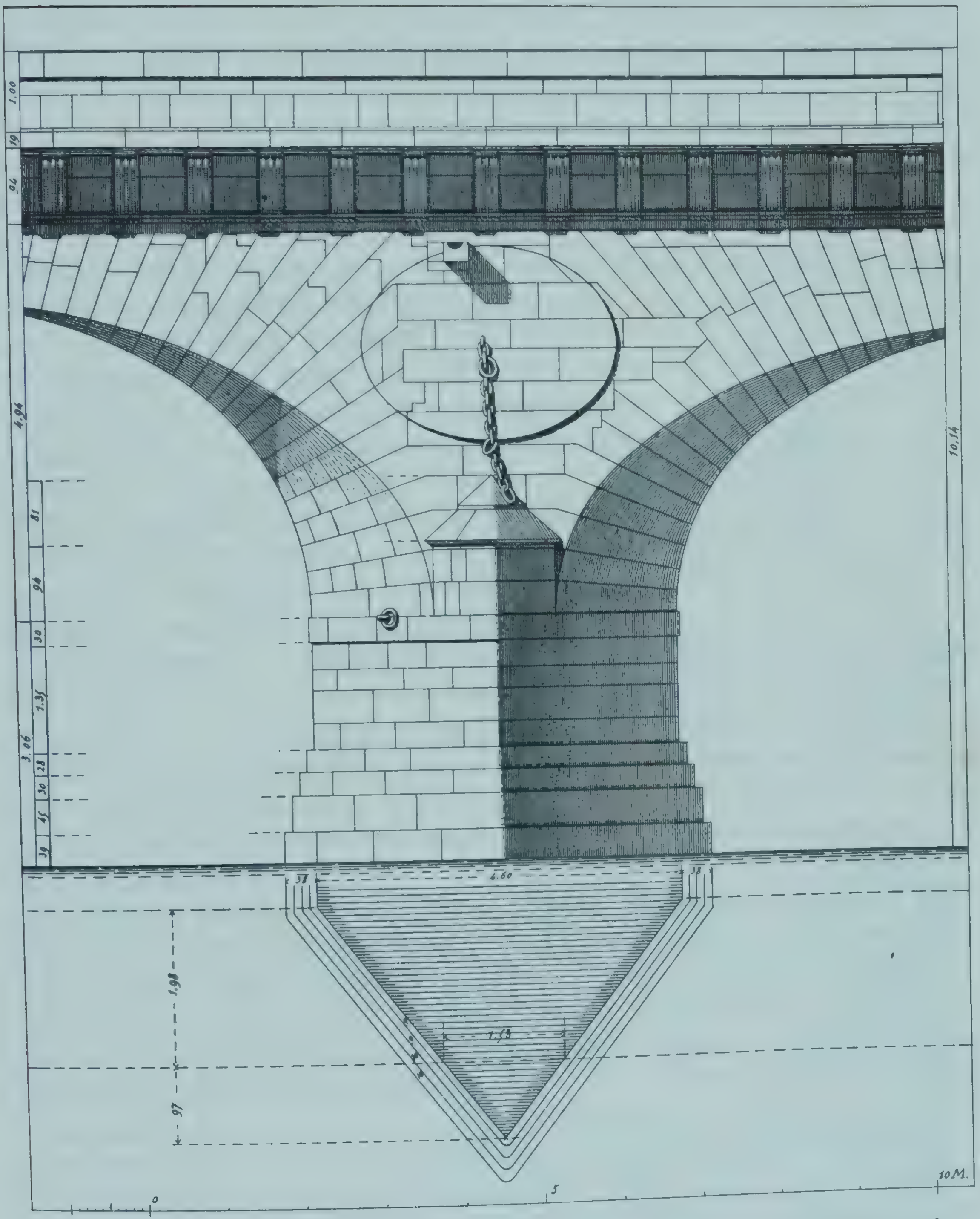

FIGURE 272—*The Pont Henri IV at Châtellerault (1565–1609); downstream face of a pier, showing the splay of the arches.*

gested, and the house-sites could be let at substantial rents. Although the houses reduced the width of the roadway over the bridge from 20 ft to 12, these rents were too high to be forgone. The houses were of wood, and were on many occasions partly or wholly destroyed by fire. The last of them was demolished in 1762. The Pont Notre-Dame retained its houses into the twentieth century.

IV. STRUCTURAL THEORY

Bridge-building in Roman, medieval, and even in Renaissance times owed nothing to abstract science. Even for the vaulting of the great abbey and cathedral churches—a far more delicate matter—there is no evidence of theory in the modern sense. By sound deduction from progressive movements and defects in actual structures, and some deliberate experiment, particular problems were solved; but the contemporary statical theory in general terms would have been a quite inadequate guide to anything like the same bold, economical disposition of material. Even for Galileo (1564–1642) the practices of ship-builders and pump-makers presented questions to be studied in the same way as natural phenomena [11]. Craftsmen could tell him what they did, but they could not explain scientifically why large ships had to be disproportionately massive as compared with small boats, or why a suction-pump failed to lift water from a depth of much over 30 ft. The theory of dimensions and the properties of the vacuum he had to discover for himself. Galileo was the first to discourse in mathematical terms on the strength of materials. He was, however, not the first to make experiments in that field, for Leonardo da Vinci's notebooks contain sketches, accompanied by rough calculations, of tests to measure the tensile strength of wires (p 250), and the strength and stiffness of small columns and beams of given dimensions. Leonardo also showed an apparently novel appreciation of the parallelogram of forces, with the directions of the forces inclined at various angles, and of the moments of forces and of their resultant. On all these points his views were in advance of those generally held at that time. In no case did he reach general conclusions, but neither did anyone else for the next two centuries [12].

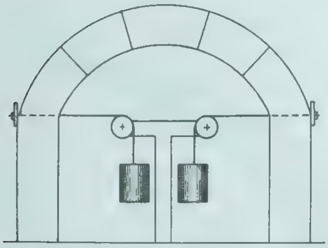

FIGURE 273—*One of Leonardo's drawings, illustrating his study of the horizontal thrust of an arch upon its supporting walls.*

On the stability of arches, too, Leonardo seems to have held views far in advance of any known to have been made public until long after his day. He sketched models of loaded arches with cords arranged over pulleys to measure the horizontal thrust (figure 273). He thus disproved the dangerous fallacy that the load on a semicircular arch follows the direction of the arch ring, and so is transferred to the abutment as a vertical force with no horizontal component. So confident was he that in 1502 he proposed in writing to the Sultan of Turkey to build a bridge across the Golden Horn, in a single segmental span of 700 ft and a rise of 180 ft. On plan the sides were to be curved outward to widely spread abutments, the springings situated deep within an excavation of vast size and depth. Leonardo's sketch is small and diagrammatic; but the weight, reactions, thrust, and stresses have been calculated on the optimistic assumption that Leonardo would have made the axis of the rib coincide—or nearly so—with the line of thrust for dead-weight [13]. The thickness at the crown would have been about 30 ft, and the bridge would have taken about three-quarters of a million tons of stone. It would have been impossible to frame the centring required, or to build a coffer-dam to resist a head of perhaps 100 ft of water, nor could such a vast project have been organized and financed. No single-span masonry-arch of such great size has ever been constructed, or is likely to be.

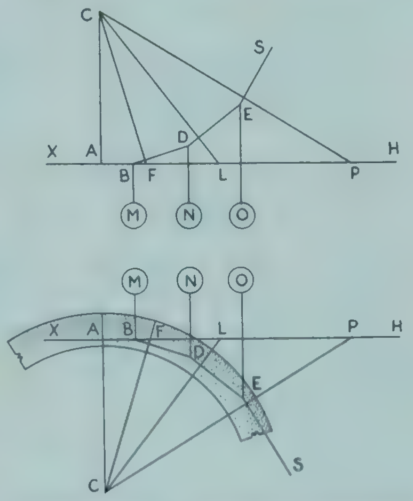

FIGURE 274—*La Hire's force diagram and link polygon.* (Above) *Forces in a loaded chain;* ABDES *is the profile of a loaded cord. The rays* CA, CF, CL, *and* CP *are at right-angles to* AB, BD, DE, *and* ES *respectively, and when produced cut* AB (*or* AB *produced*) *at* A, F, L, *and* P. (Below) *forces in an arch.*

The first serious attempt to devise a theory of the arch, one quoted by theoretical writers a century later, was the 'smooth voussoir theory' put forward by Philippe de La Hire (1640–1718) in a little textbook on mechanics (1695) (figure 274) [14]. The sides of the triangles CAF, CFL, CLP represent to scale the forces acting at B, D, and E respectively, and are in fact the triangles of forces for these points. La Hire had developed in ABDES a link-polygon, and in CAFLP a force-diagram, which were reciprocal figures. He had, indeed, laid the foundation of graphic statics; but a century and a half passed before engineers realized the generality and power of the methods of computation that could be based on the use of such diagrams.

Inverted (figure 274), the link-polygon becomes the line of pressure for an arch-ring in which the force acting across each joint is at right-angles to the meeting-faces of the stones, and so causes direct compression without evoking any frictional resistance. This was a simple case to study; it thus assumed an importance it did not deserve and tended to obscure the real problem of the arch. For even ignoring the adhesion at a mortar joint, the friction between two surfaces of stone, however smoothly worked, is high.

It will be noticed that to keep the line of pressure within the profile of a semicircular arch-rib the loads M, N, O, . . . would have to increase rapidly in magnitude as the voussoir to which they apply is farther round the rib from the crown, until, for the last voussoir standing on a horizontal surface, the vertical load that would prevent it sliding in the absence of friction or horizontal restraint would have to be infinitely large. Clearly this in no way represents the actual state of affairs. La Hire realized this, and confined his theory to that part of the arch in which the joints were inclined to the horizontal at an angle greater than 45°. The fact is that the spandrel-filling can exert a considerable resistance. Modern tests have shown that this is so even when the filling is of earth, once it has been packed down tightly by time and traffic.

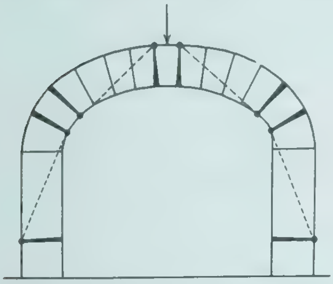
FIGURE 275—*Diagram illustrating Danisy's study of the virtual hinges in a failing arch.*

The ideal profile for an arch-ring of constant thickness, carrying only its own weight, would clearly be a catenary.[1] The loading of an actual arch seldom approximates to this condition. Nevertheless the idea gained currency in the early eighteenth century, or earlier, that no arch could be considered stable unless a true catenary could be drawn within its profile.

A sounder approach to the problem was made by a Frenchman named Danisy, who reported in 1732 the results of some tests he had carried out with sets of model voussoirs made of plaster. He found no tendency for the voussoirs to slide but noted that, when unevenly loaded, the arch-rib opened at certain joints on one edge, forming a virtual hinge at the other. If loading was increased, rotation about such hinges occurred, and the arch collapsed (figure 275) [15]. It was by the development of this view of the stability of the arch that theory in fact advanced.

V. THE PONT-Y-TY-PRIDD

The history of bridge-building in this period cannot end more appropriately than with the story of the building of a remarkable eighteenth-century bridge, the name of which is perpetuated in that of the Welsh township of Pontypridd. The river Taff at this point was difficult to ford, and impassable in winter. Glamorganshire was being industrialized and Herbert, Lord Windsor, owner of the land on both sides of the river, was granting leases for mining iron and coal. No local builder was found willing to build a bridge at such a place until William Edwards (1719–89), who combined the occupations of minister of religion and farmer, undertook to build and maintain one for seven years for the sum of £500. He employed local masons to build stout piers in the bed of the river to carry three or four arch spans. The bridge stood for about two years before it was swept away by a flood.

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[1] The curve described by a slack rope or chain suspended by its ends.

Edwards then decided that he must avoid piers in the stream, and planned to build a single arch with a span of 140 ft, curved to a radius of 175 ft. A fellow minister-cum-wheelwright, named Thomas Williams, is believed to have shared Edwards's second venture, doubtless erecting the centring. The bridge was built, or nearly so, when a flood carried away the centring and this second bridge collapsed. Edwards made a third attempt, with stronger centring. The bridge was completed and the centring struck while the river was still low; but during flood and storm about six weeks later, in November, 1754, the haunches sank, the crown rose, and the arch collapsed. Edwards seems to have realized why his bridge failed: the haunches were too heavy for the light crown. He started to build the fourth bridge. He formed the haunches with cylindrical voids surrounded by rings of masonry keyed into the spandrel-walls at both sides of the bridge (figure 276). These both lightened the work, where weight had been excessive, and ensured greater firmness. This fourth attempt proved successful.

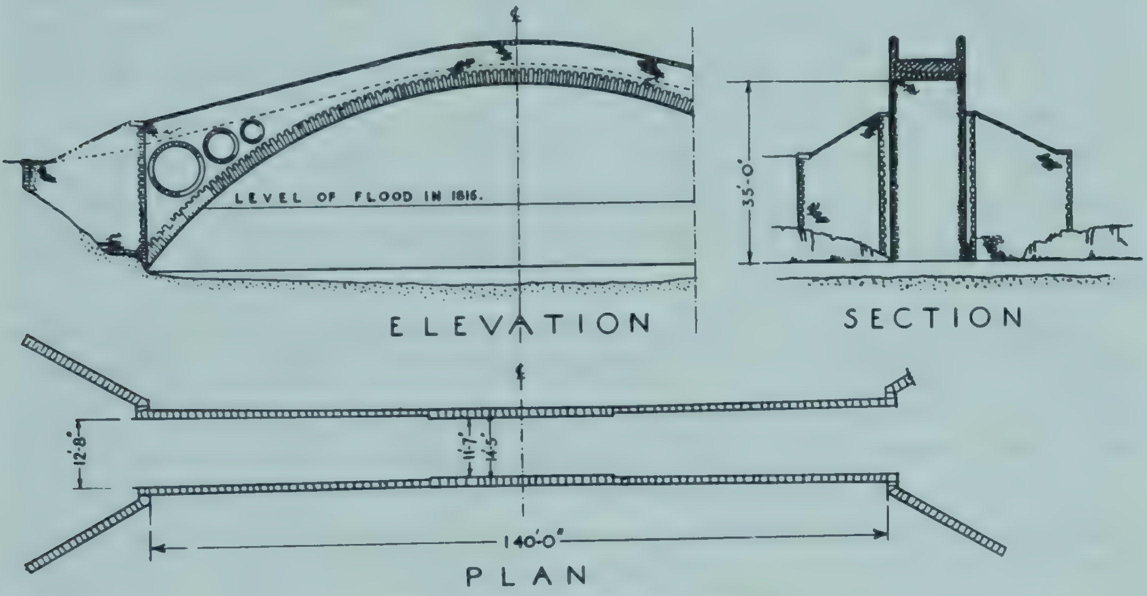

FIGURE 276—*The Pont-y-Ty-Prydd.*

The bridge was opened in 1756, and still stands. It is now by-passed by a modern bridge, carries only foot-traffic, and has been scheduled as an ancient monument [16].

Although some extra money was collected, Edwards must have lost heavily on his contract. However, having established a reputation as a builder of bridges, he was commissioned to construct others in south Wales; but never again did he attempt anything so bold as the Pont-y-Ty-Pridd.

Whether Edwards had seen illustrations of ancient bridges perforated in the spandrels, or hit on the idea himself, is not known. A drawing of the bridge that he sent with a letter to the Society of Antiquaries in 1760 was later found among the papers of John Smeaton (1724–92) now in the possession of the Royal Society [17]. This find started the false assumption, duly repeated in many histories of bridges, that Edwards had consulted Smeaton, and perforated the spandrels on his advice. Smeaton in 1755, still a maker of instruments, was paying the visit to Holland that preceded his entry into civil engineering as a career. We may be certain that Edwards did not consult him or any established authority.

Edwards's arch-ring is of stones, only about 18 in deep, with wide, wedge-shaped joints, filled with mortar made with a local hydraulic lime. It is probable that the arch-ring, the rubble fillings, the roadway, and the parapet-walls were, once the mortar had hardened, virtually monolithic. Even so, they are the equivalent of an arch-ring at most 3 ft 6 in deep. On Henri Gautier's rule the depth at the crown should have been 9 ft 4 in. Even Perronet, at that period, would have made it 6 ft. It is, therefore, not surprising that later writers often tried out their theories on the Pont-y-Ty-Pridd.

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17

CANALS AND RIVER NAVIGATIONS BEFORE 1750

A. W. SKEMPTON

I. INTRODUCTION

It is well known that the English canals of the eighteenth and early nineteenth centuries served as the arteries of the industrial revolution, but even in pre-industrial times the rivers and canals of Europe and Asia played a significant part in trade and commerce. One reason for this is that rivers (and canals are but extensions of river-systems) form the most natural inland routes to and from sea-ports. Moreover, so long as men and horses provided the only practical source of motive power for inland transport, heavy and bulky goods could be carried more economically and efficiently on water-ways than by any other means.

To illustrate this point quantitatively, the loads that can be carried or drawn by a single horse are set out in the table below. The gain in mechanical efficiency was partially offset by the greater capital expenditure required for the engineering works of the canal and river navigations; nevertheless the average cost of carriage by water in eighteenth-century England, for example, was rarely more than half and often only a quarter of the cost by road [1]. And the roads were frequently impassable for commercial traffic in winter.

Typical loads carried or drawn by a single horse

Pack-horse		$\frac{1}{8}$ ton
Wagon	on 'soft' roads	$\frac{5}{8}$ ton
	on macadam roads	2 tons
Wagon on iron rails		8 tons
Barge	on river	30 tons
	on canal	50 tons

II. TRANSPORT CANALS IN CHINA

The earliest major civilizations were in the valleys of the Euphrates, Nile, Indus, and Huang-Ho, and these great rivers provided a ready means of transport in addition to their life-giving supply of water for irrigation. The Phoenicians and the Greeks were maritime peoples, while the Romans chiefly made use of the many naturally navigable rivers in their empire. Apart from a few notable canals such as that from the Nile to the Red Sea, cut by order of Darius *c* 510 B.C., and several in France, Lombardy, and the Netherlands made during Roman times, the first sustained effort in canal-construction was made by the Chinese [2]. Among the more important of their works are the Ling Ch'u canal in Kuangsi (215 B.C.), the 90-mile-long canal from the Han capital Ch'ang-an to the Yellow River (133 B.C.), the Pien canal in Honan (A.D. 70), the Shanyang canal in Chiangsu (A.D. 350), and the first sections of the Grand Canal completed in 610. This had a total length of 600 miles, and along its banks ran an Imperial road planted with elms and willows. It served to transport grain from the lower Yangtze and the Huai to Kaifeng and Loyang. Under the T'ang dynasty in the eighth century the traffic on the canal was known to exceed 2 million tons annually.

In most cases the land traversed by these canals had a small gradient, and water-levels could readily be controlled by single gates separated from each other by considerable distances. For instance, on the Pien canal in A.D. 70 the engineer Wang Ching built the gates typically some 3 miles apart. They consisted of stone or timber abutments, each with a vertical groove into which squared logs of timber could be lowered or raised by ropes attached to their ends (plate 18). These simple stop-log gates evidently derived from the sluices used on irrigation canals. On the smaller transport canals, and especially in places where an appreciable difference in land-level had to be overcome, a double slipway was usually built, over which the barges were hauled. References to this device occur in Chinese literature at least as early as A.D. 348.

Occasionally a more elaborate gate was adopted, in which a solid door could be raised or lowered by a windlass. Two of these were built by Ch'iao Wei-Yo in 984 to replace a double slipway, during the remodelling of a section of the Grand Canal, and by placing the gates only 250 ft apart he created the first known example of the canal-lock: a device of fundamental technological importance. With single gates widely spaced along a canal or river considerable delays and great losses of water are involved in waiting for the levels to equalize after any particular gate has been opened, unless the difference in level is slight. With the lock, however, only the comparatively small volume within the lock-basin has to be filled or emptied, and the water-level in the long reaches or pounds between two locks is never altered.

It is rather curious, therefore, to find that little use was made of the lock in China. Its later development was entirely due to western engineers. Yet, if the Chinese remained content, in general, with their stop-log gates and slipways, they nevertheless achieved canal-works on a most impressive scale. Outstanding among these was the construction, between the years 1280 and 1293, of the northern branch of the Grand Canal from Huaian to Peking, having a length of 700 miles. Parts of this utilized existing rivers, and other sections were 'lateral' canals; but the section crossing the Shantung foothills, completed in 1283, was the earliest example of a 'summit-level' canal. A lateral canal has a continuous fall in one direction and, with intakes from the river alongside which it runs, there are few problems in water-supply. The conception of a lateral canal is relatively simple, since it is essentially an improvement of an existing river. In contrast, the idea of taking a canal over the summit of a watershed dividing two rivers requires bold imagination and considerable technical skill in providing an adequate water-supply at the summit. The Shantung section of the Grand Canal linked the Yellow River with a group of lakes, situated some 100 miles to the south at approximately the same elevation as the river. But over a short length the intervening land rose to a height of about 50 ft above the river and the lakes. The upper part of the canal was taken in a cutting with a maximum depth of 30 ft, yet this still left a fall of 20 ft to the north and south. To provide for the inevitable losses of water occasioned by operating the gates, two small rivers situated to the east, higher up the foothills, were partially diverted to flow into the summit-level. The engineers of this notable undertaking were Li Yueh and Lu Ch'ih.

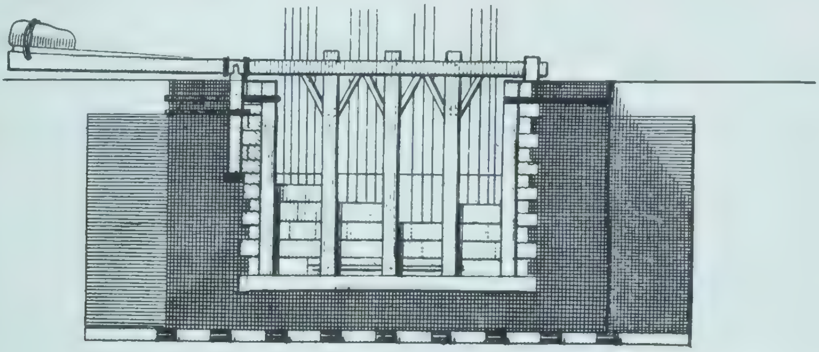

FIGURE 277—*Section of a typical stanch or flash-lock. From Belidor, 1753.*

III. MEDIEVAL CANALS AND RIVER WORKS

At the time when the Grand Canal of China was completed, water-transport in Europe was still in a primitive state. Few canals had been constructed, and rivers were chiefly used as a source of power for water-mills. On many rivers each mill had its weir, to provide an adequate head of water for the mill-wheel, and these weirs were a serious obstacle to navigation. In the later Middle Ages, however, important developments took place in the Netherlands, as we shall see, while throughout the more commercially active countries of Europe improvements were made in the rivers by building stanches in the weirs and also at intervals along the river, between the mills, to reduce the gradient and increase the depth of water in the shallow places [3].

A typical stanch (also called a flash-lock or navigation-weir) is shown in figure 277. When a boat wished to pass, the wooden boards or 'paddles', with their long handles, were lifted out, and after the rush of water had somewhat abated the balance-beam, with the vertical posts which had supported the paddles, could be turned aside to leave a clear opening. Often the boats had to be hauled through against the flow, by a winch placed on the bank upstream of the stanch; in travelling downstream boats would find the 'flash' of water released by opening the stanch a help in crossing any shoals below it.

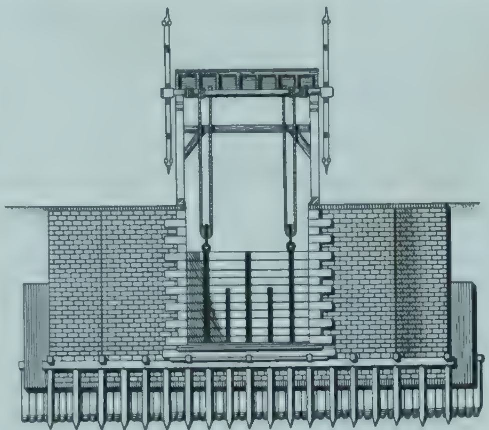

FIGURE 278—*Section of a typical 'portcullis' sluice. From Belidor, 1753.*

The early history of stanches is obscure, but it is practically certain that they were in existence on a number of rivers in Flanders,[1] Germany, England, France, and Italy before the end of the thirteenth century. A reference to the winch for a stanch on the Thames at Marlow occurs in 1306. The oldest complete account of the Thames navigation between Oxford and Maidenhead, in 1585, shows twenty-three stanches; all but four were situated in the weirs of the mills on this 62-mile stretch of river [4]. Many of these stanches were still in place in the mid-eighteenth century, while as recently as the early nineteenth century twenty-two stanches were to be seen on the Marne between Châlons and Paris.

The very existence of Holland depends upon the dikes and drainage canals, and it is not surprising that some of the canals were enlarged and suitably equipped for transport at an early date. Originally the drainage canals had outlets through the dikes controlled by sluices. In some cases goods had to be transhipped over the dike, and in other places boats were hauled over a double slipway similar to those in China.[2] Perhaps the first examples were at Het Gein and Otterspoor, built in 1148 on the Nieuwe Rijn canal near Utrecht. Where hydraulic conditions permitted, an obvious improvement was to make the sluice-gate large enough for the passage of boats. These navigation sluices in Holland were of the lifting-gate or portcullis type shown in figure 278. When the tide in the estuary or river was at the same level as the water in the canal, the gate was raised by a windlass and boats could pass through. At other states of the tide a difference in water-level existed across the gate. To safeguard the sluice from under-seepage the foundations and abutment-walls were extended, typically 20 or 30 ft beyond the gate and also well into the body of the dike. Figure 278 represents a sluice built in 1708; it will be seen that the danger of under-seepage is further prevented by sheet-piling. This was a characteristic feature of construction in the sixteenth century and later, but seems to have been unknown to medieval engineers. A *magna slusa* at Nieuport, mentioned in 1184, may have been of the portcullis type, as also the sluice at Governolo on the river Mincio, built in 1188–98 by Alberto Pitentino, and that at Gouda of *c* 1210.

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[1] Possibly as early as 1116 on the river Scarpe.

[2] The double slipway was used also in Italy, and one was built in 1437 at Fusina where the river Brenta enters the lagoon south of Venice. This slipway, as reconstructed in the sixteenth century, is illustrated by Zonca [5]. The slipway at Fintelle, in Flanders, remained in use until 1824.

The next step was of vital importance. It involved building two sluice-gates, one behind the other, enclosing a basin or chamber and thereby forming a lock. The first example that can be dated with certainty was built in 1373 at Vreeswijk, where a canal from Utrecht enters the river Lek [6]. From regulations of 1378 and 1412 we learn that the Vreeswijk lock was operated three times weekly, at 2 o'clock in the afternoon [7]. First the outer gate was wound up, and the boats from the river-harbour entered the large basin of the lock. The outer gate was then closed and the inner one raised, and when a level had been made the boats were hauled through into the canal. The inner gate was then closed again and the outer gate opened, and in due course the boats that had been waiting in the basin could pass into the river. This leisurely procedure was not without advantage to the townspeople of Vreeswijk since it provided the boatmen with ample time for shopping and gossip. It is possible that a similar lock had been built somewhat earlier at Spaarndam, but it was only in the later fourteenth century that this form of construction became widely adopted. Examples include basins at Delfshaven (1389) and Schiedam (1395). At Gouda in 1413 a lock was built by Jan van Rhijnsburch with a triple set of gates.

A large basin was typical of the early Dutch tide-locks and is essential for intermittent working, but in 1394–6 a lock was built at Damme, near Bruges, in which the chamber formed by the two gates and the masonry side-walls was 100 ft long and 34 ft wide. This suggests that the lock at Damme was operated as often as any boat arrived there, and it is the earliest lock with what may be regarded as modern proportions.

By 1400, therefore, important advances had taken place in the construction of locks. But those made in the Netherlands were intended only to overcome differences in water-level, and the first locks to overcome differences in land- as well as water-level were built on the Stecknitz canal, 1391–8 [8]. This is also the oldest summit-level canal in Europe, and therefore a work of considerable historical interest.

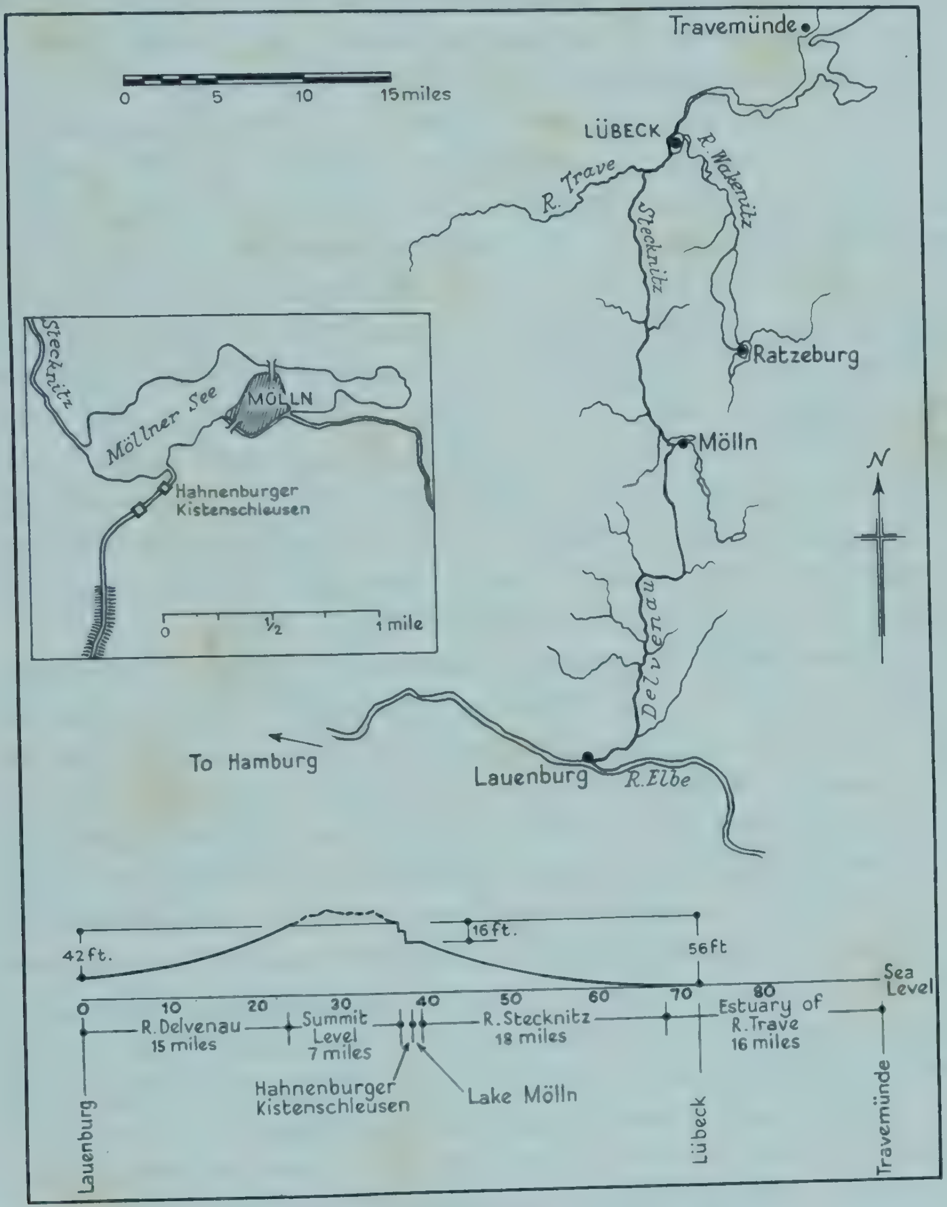

FIGURE 279—*Map and longitudinal section of the Stecknitz canal, 1391–8.*

In the early fourteenth century the river Stecknitz had been made navigable from Lake Mölln down to Lübeck, a distance of 21 miles and a fall of 40 ft, with four stanches. In 1391 an extension of this waterway southwards to Lauenburg on the Elbe was begun, to establish a link between the Baltic and the North Sea (figure 279). From the lake a canal was dug, rising 16 ft in a distance of less than half a mile, then running horizontally for 7 miles in a cutting with a maximum depth of about 12 ft to meet the river Delvenau. This river falls 42 ft in a distance of 15 miles to Lauenburg. It was rendered navigable by eight stanches. The sections south of the summit (formed by the Delvenau) and north of Lake Mölln (formed by the Stecknitz) naturally had an adequate water-supply. The steep section between the summit-level and the lake, however, was largely dependent for its supply upon water seeping from the sandy soil in which the cutting had been excavated, and with single-gate sluices or stanches the loss of water would have been excessive. In order to overcome this difficulty two locks were built, known as the Hahnenburger Kistenschleusen. Each could contain ten small barges (35 ft long and of 11-ft beam) and, like the tide-lock at Vreeswijk, they were operated every second or third day. The men responsible for this scheme are not known, but the close connexion between Lübeck and the Netherlands, through the Hanseatic League, may be significant.

The next development of importance took place in Lombardy soon after 1450, but we must first note the work carried out there in the early fifteenth century [9]. Between 1179 and 1209 a canal was constructed with an intake on the river Ticino, whence its course ran south to Abbiate and then east to Milan. It fell 110 ft in 31 miles (figure 280). Initially the canal was designed for irrigation, but in 1269 its cross-section was enlarged and sluices or stanches were built in the various weirs along its length. The canal was then known as the Naviglio Grande. It did not enter the city, but ended in a basin just outside the western wall.

In 1387 plans were being prepared for the new cathedral at Milan, and when construction began the chief building-material was marble from quarries near Lake Maggiore. This was brought down the Ticino and along the Naviglio Grande. How the marble was at first carried from the canal-basin to the cathedral is not clear, but early in the fifteenth century a canal was made linking the Naviglio Grande with the old moat, which had surrounded the city at an earlier date when its area was much smaller. This moat passed quite close to the cathedral. By means of a single-gate sluice in the link canal, situated alongside the Via Arena, boats could pass from the Grande to the mason's yard. But the water-level in the moat, which was fed by the Seveso running in from the north, was several feet above that of the canal. Consequently, whenever the sluice was opened the water-level in the moat had to fall to that of the canal; when the boats had passed the sluice, the moat had to fill again before they could proceed along it. In 1438 this inconvenient arrangement was improved by the construction of a second gate in the link canal along the Via Arena, thus forming the first pound-lock in Italy. The engineers responsible for this work were Filippo da Modena and Fioravante da Bologna, and it appears that before 1445 they had built a second lock near Sant' Ambrogio on the old moat which, by now, had been enlarged and was known as the Naviglio Interno.

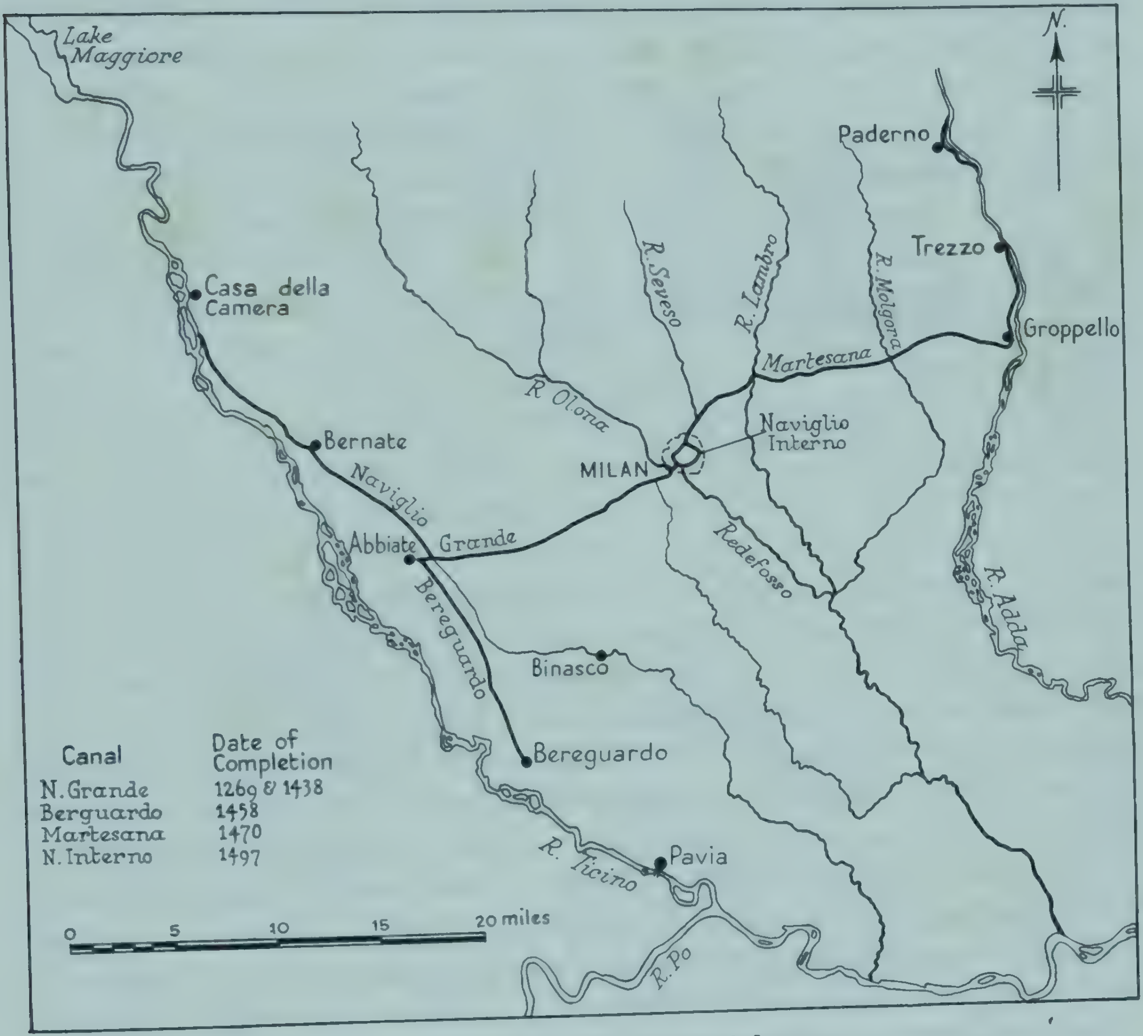

FIGURE 280—*Map of canals near Milan before 1500.*

IV. CANALS OF THE ITALIAN RENAISSANCE

The canal-works in Lombardy of the later fifteenth century mark a new epoch in canal-construction. In 1451 Bertola da Novate (*c* 1410–75) was appointed ducal engineer of Milan, and one of his first tasks was to consider the possibilities of building a canal from Milan to Pavia on the river Po [10]. In 1359 a small irrigation canal had been constructed from Milan as far as Binasco, about halfway towards Pavia. The question of enlarging and extending this canal was naturally investigated, but Bertola concluded that it would be too difficult an operation and recommended instead that a canal be cut from Abbiate, on the Naviglio Grande, southwards to the village of Bereguardo, with a land-portage to the banks of the Ticino (figure 280). Work began in 1452. By 1458 the canal was completed, with a length of 12 miles and a fall of 80 ft taken in 18 locks; it was the earliest canal in which a considerable gradient was controlled entirely by pound-locks.

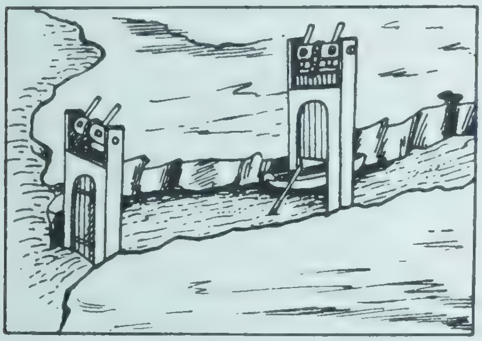

FIGURE 281—*Sketch of a lock with portcullis gates, c 1470.*

While the Bereguardo canal was under construction, Bertola was consulted on the construction of five locks near Parma. These were built between 1456 and 1459 under the supervision of an assistant, Bertola visiting the site from time to time. Meanwhile in 1457 he prepared plans for a canal joining Milan to the river Adda, east of the city. This canal, constructed between 1462 and 1470 and known as the Martesana, had an intake on the Adda at Trezzo, where a large weir was constructed. The canal then proceeded alongside the river for a distance of some 5 miles until a point was reached at which it could turn westward over the Lombardy plain to Milan. The great masonry wall separating the canal from the river in the first 5 miles remains today much as it was originally built. The canal was carried over the river Molgora on a small three-arch masonry aqueduct, the earliest known example, and the stream of the Lambro was carried under the canal in a culvert of the type illustrated in figure 294. By careful planning Bertola was able to lay out this 24-mile-long canal with only two locks. Boats entered a basin or dock near San Marco in Milan.

By this time knowledge of the pound-lock was becoming general in Italy. In his book *De re aedificatoria*, completed during the 1460s and published in 1485, Leone Battista Alberti (1404–72) gives an account of a lock with a pair of gates separated by a distance equal to the length of a boat [11]; it is possible that he was in fact describing the locks built by Bertola, unquestionably the leading canal engineer of his time. In 1481 the brothers Domenico da Viterbo built a lock at Stra on the canal joining Padua to the river Brenta [12], and in 1491–3 several timber locks were built by 'an engineer of Milan' on the canal near Bologna [13]. Few details are known of these early Italian locks, and the only contemporary illustration so far discovered is a sketch in the *Codice Laurenziano*, dated between 1460 and 1490 [14]. The drawing (vol II, figure 626) as a whole is difficult to interpret, but a pair of the vertical-lift gates represented may be taken as constituting a lock similar to that described by Alberti (figure 281).

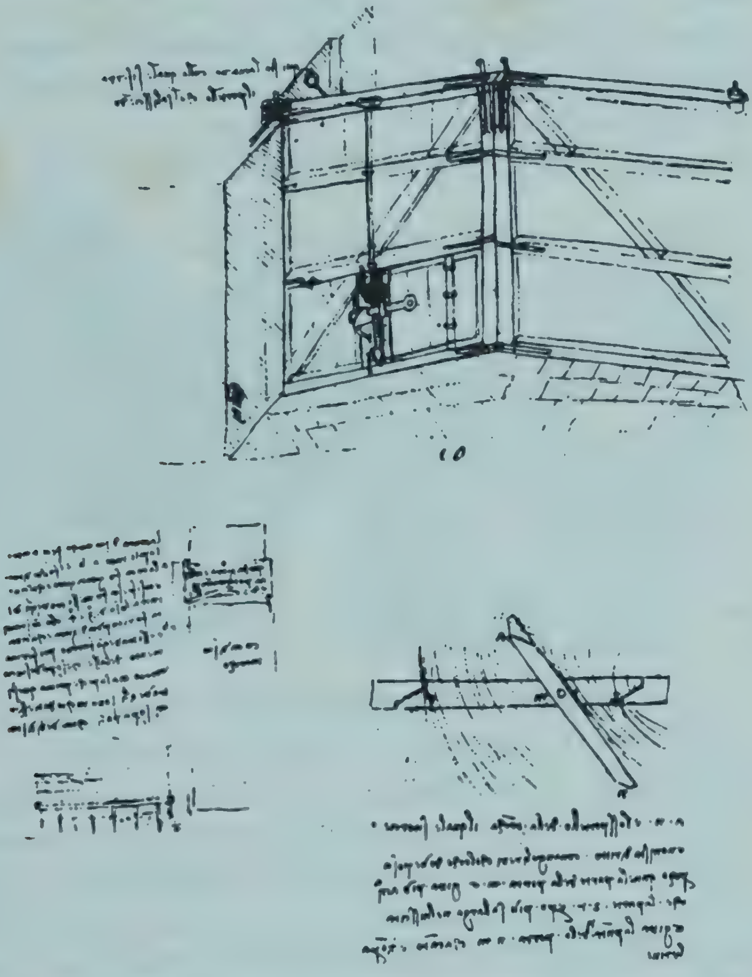

FIGURE 282—*Sketch by Leonardo da Vinci of mitre-gates for the San Marco lock, Milan. c 1495.*

The portcullis type of gate was not ideally suited to navigational purposes. It was superseded in the last decade of the fifteenth century by Leonardo's wonderful conception of the mitre-gate. Leonardo da Vinci (1452–1519) was appointed ducal engineer of Milan in 1482; some ten years later he turned his attention to hydraulics and, in particular, to the construction of six new locks on the Naviglio Interno. These were completed in 1497, and Leonardo's drawing for the gates of the lock at San Marco, situated just below the terminal basin of the Martesana canal, is shown in figure 282. In another drawing (figure 283) Leonardo shows a rectangular masonry lock 95 ft long between the gates and 18 ft wide, having a pile cut-off wall and mitre-gates, in which there are small sluice-doors, identical with those at San Marco. These drawings, which give the first complete design of a modern form of lock, are of the highest importance in the history of canal-construction.

In 1503 Leonardo went to Florence, where he was engaged upon very ambitious plans for a canal from that city to the river Arno near Vicopisano. This was to have been a summit-level canal, and Leonardo gave careful thought to the problem of an adequate water-supply at the summit [14]. His project, however, was in advance of its day, and the first summit-level canal of real importance was not built until the early seventeenth century, in France.

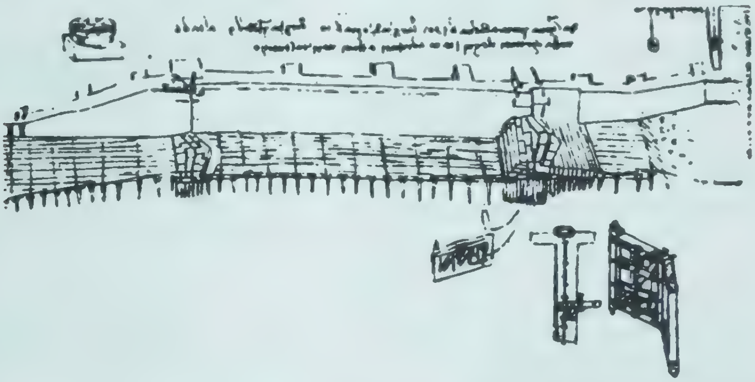

FIGURE 283—*Leonardo's sketch of a longitudinal section of a lock with mitre-gates.*

The Martesana canal had successfully linked Milan with the river Adda, but upstream of Trezzo the river was impassable and it was clearly desirable to by-pass this section, to enable navigation to continue up to Lake Como. In 1518 Benedetto da Missaglia designed a lateral canal for this purpose with headworks near Paderno, where there was to be a diversion-weir 14 ft high at a location chosen after borings had been made in the river bed. The canal would then run in an excavation on the right bank, to re-enter the Adda at a point situated 3000 yd downstream and 90 ft lower than the intake. Ten locks were proposed and the amount of water admitted to the canal was to be regulated, all the surplus above a predetermined maximum flowing back to the river over spill-ways in the canal bank. Work began in 1519 and it seemed that this fine example of river navigation would be successfully completed. In 1515 Milan had come under the rule of Francis I of France and it was by his order that the canal had been started. In 1522, however, Francis lost Milan to the Emperor Charles V; the main driving force was thus removed, and work on the canal ceased.

In 1584 plans were prepared for a canal between Milan and Pavia, but in the following year a serious flood damaged the intake of the Naviglio Grande. Attention had therefore to be directed immediately towards the reconstruction of this important component of the Lombardy canal-system. The work was entrusted to Giuseppe Meda (*c* 1540–99), who took the opportunity of completely remodelling the old intake, still little changed from its medieval form. He built a weir and control-works similar in principle to those designed by Missaglia on the Adda. Meda's later career was tragic. In 1591 he prepared a new scheme for the Paderno canal, using an entirely novel form of lock, of the type later known as a shaft-lock [15]. After various mishaps and interference from the authorities in Milan his plans were only partially carried out before his death. Meanwhile in 1595 he had drawn up proposals, complete in all details including the locks, culverts, aqueducts, and bridges, for the canal between Milan and Pavia. A year later these proposals were accepted, but work had barely started before the engineer died and this scheme too was abandoned.

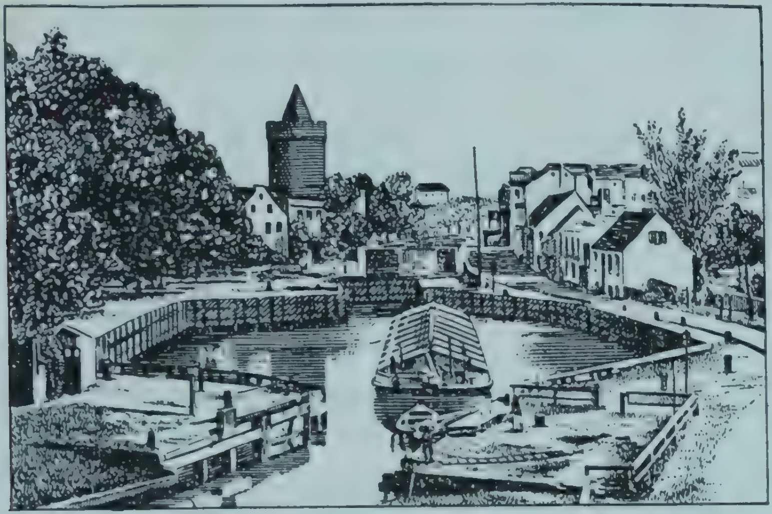

FIGURE 284—*Lock at Brandenburg, 1548–50.*

V. THE POUND-LOCK IN THE SIXTEENTH CENTURY

The increasing importance of canal and river navigations in the sixteenth century is reflected in the widespread adoption of the mitre-gate pound-lock. The first examples, as we have seen, were completed by Leonardo in 1497 on the Milan canal. These were followed in 1518 by Missaglia's designs for the locks on the Paderno canal, and by three locks near Bologna built in 1548 by Giacomo da Vignola (1507–73). The latter were oval in plan, 100 ft long, 25 ft in maximum width, and 12 ft wide at the entrance [13].

The earliest examples in France that can be securely dated are those designed in 1550 in connexion with improvements of the rivers in the neighbourhood of Bourges. Detailed specifications of these locks still exist in the archives at Bourges [14]. In all, fifteen locks were required, two of masonry on the river Yèvre, four similar ones on the river Cher, and nine of timber construction on the river Auron. The locks were rectangular with a length of 90 ft between the gates and a width of 13 ft. The floor and side walls extended 15 ft beyond each gate, beneath which sheet-pile cut-off walls were constructed.

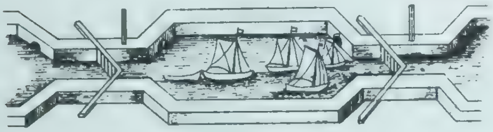

FIGURE 285—*Sketch of a lock on the Brussels canal*, c *1560*.

In the same period improvements were being made on the Havel and Spree in the Mark Brandenburg [16]. Work began on two locks at the towns of Rathenow and Brandenburg in 1548, at Spaarndam in 1572, and in Berlin in 1578. The lock at Brandenburg, with its large octagonal basin and timber walls, still exists (figure 284), but the type of gate originally used is not known. A sketch by Tilemann Stella (1524–89) of the locks that he built on the Mecklenburg canal between 1572 and 1582 shows mitre-gates and a rectangular chamber 18 ft wide and 90 ft long. He had visited the Netherlands in 1561 to study hydraulic engineering and would have seen the Brussels canal, completed in that year.

This important canal, begun in 1550, is described in the next section (p 452). Here it may be noted that the works included four locks of octagonal shape, 200 ft long and 70 ft wide, with falls varying from 6 ft to 10 ft. One of these locks is shown in figure 285. It can be seen that there were mitre-gates and that the chamber was emptied and filled by means of culverts in the walls. This is the earliest known example of the ground-sluice, a device enabling the basin to be operated more rapidly and with less disturbance than with the usual sluice-doors in the lock-gates.

In England the first pound-locks were constructed in 1564–7 by John Trew on a lateral cut beside the Exe, known as the Exeter canal [17]. Like the locks on the Brussels canal, on the Havel, and the old tide-locks in Holland, those at Exeter had a basin of sufficient size to hold several boats. They were 189 ft long by 23 ft wide. A manuscript sketch shows three vertical-lifting sluice-paddles in each leaf of the mitre-gate at the upstream end of the lock [18]. The lower end, however, was closed by a single gate. This arrangement also occurs in the sixteenth-century Italian lock on the Brenta, illustrated by Zonca (vol II, figure 625).[1] Both upper and lower mitre-gates, however, were provided in the lock built 1571–4 on the Lea, near London, at Waltham Abbey, where

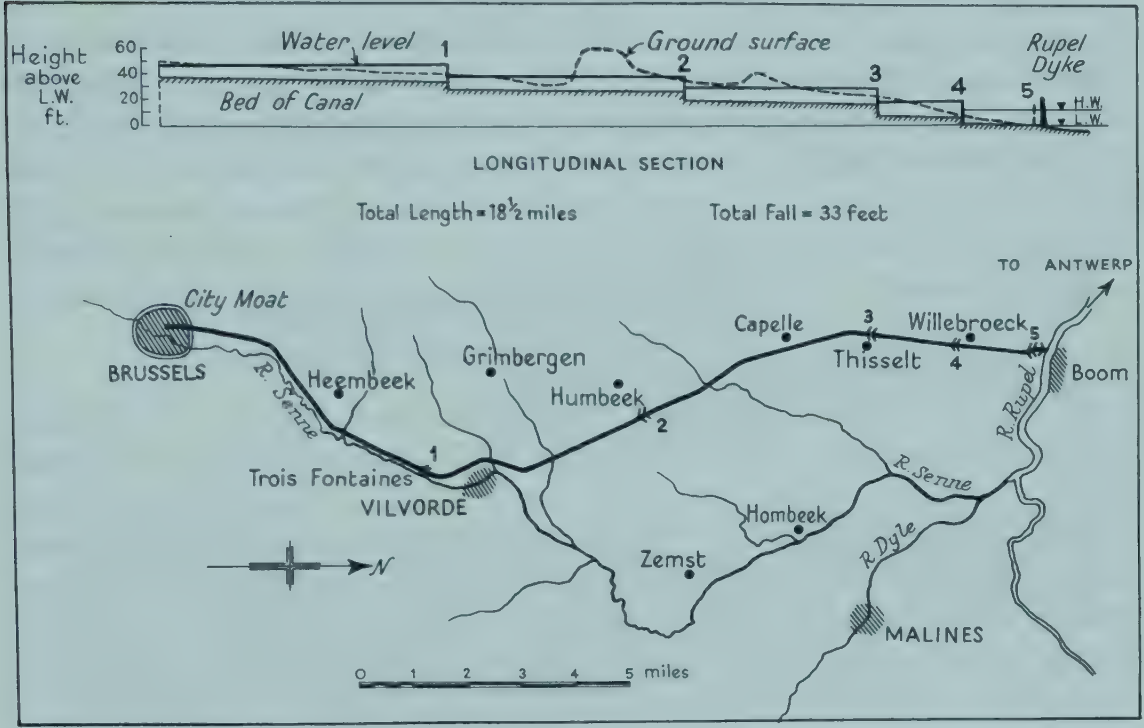

Figure 286—*Map and longitudinal section of the Brussels canal, 1550–60.*

> . . . a rare device they see,
> But newly made, a waterworke; the locke
> Through which the boates of Ware doe passe with malt.
> This locke contains two double doores of wood,
> Within the same a cesterne all of Plancke,

---

[1] Vittorio Zonca (1568–1602), an architect-engineer of Padua, does not give the location of this lock in his book [5], but says that gates of the type shown are to be found in the locks at Padua and Stra (i.e. on the Brenta canal). There is no reason to assume that the gates built a century earlier in the Stra lock, by the brothers Domenico, were similar to those depicted by Zonca.

Which onely fils when boates come there to passe
By opening of these mightie dores.
(Vallans, 'Tale of Two Swannes', 1577.)

The first mitre-gates in Holland appear to be the triple set built in 1567, and described by Andries Vierlingh (1507–79), at Spaarndam in a new tide-lock (*Grote Haerlemmer Sluys*) 25 ft wide and 122 ft long [19]. There may have been earlier examples, however, for Simon Stevin (1548–1620), writing at Leiden in 1617, says that the mitre-gate pound-lock 'has been in use for a long time' [20].

Finally, it is interesting to note that in Sweden eleven locks were built between 1603 and 1610 as part of the canalization of the river Eskilstuna between Lakes Hjälmar and Mälar (p 455) [21]. Thus, by the beginning of the seventeenth century knowledge of the canal-lock had spread practically throughout Europe.

VI. CANALS IN FLANDERS

Of the canals built in the sixteenth and seventeenth centuries, the Brussels canal was the first of importance to be constructed outside Italy [22]. Navigation had long existed between Brussels and Antwerp along the rivers Senne, Rupel, and Schelde. From time to time during the Middle Ages improvements were made in the Senne navigation, but in 1531 it was decided to cut a canal from Brussels to Willebroeck on the Rupel (figure 286). This would have a length of 18½ miles, which was almost half the distance that boats had previously to travel. Some of the towns on the old route opposed the plan, fearing a loss of trade, but by 1550 agreement had been reached and work was started under the direction of Jean de Locquenghien (1518–74). The fall of 34 ft between Brussels and high-water mark in the Rupel was taken in four locks (p 450). These locks were large enough to hold twelve of the small coasting-vessels using the canal, and the depth of water provided was 5 ft. Seven streams were taken beneath the canal in culverts, four road-bridges were built, and one section of the canal ran in a cutting 2 miles long with a maximum depth of 30 ft. For a distance of about 1½ miles between its entrance on the Rupel and the lowest lock the canal was contained between dikes raised some 10 or 12 ft above the low-lying marshland, and as completed in 1561 the canal was tidal in this reach. But excessive silting occurred, and in 1570 Locquenghien constructed at the debouchment of the canal a tide-lock with three pairs of mitre-gates.

The organization of the undertaking is known in some detail. Locquenghien as director of works received a regular salary during the period 1550–63. Adrien van Bogaerden, the surveyor and principal assistant, was also regularly employed throughout. The day-to-day supervision was carried out by two divisional resident engineers, and there was a treasurer. From time to time expert advice was sought. In this way Willem Maertense came from Holland in 1554 as a consultant on the opening of the Rupel dike at Willebroeck, and two years earlier Gilbert Van Schoonbeke of Antwerp was called in to give advice on the construction of the locks. The canal was not completed without difficulty. The contractor had trouble with the lock at Willebroeck during its construction; the lock at Humbeek failed in 1562, owing to seepage beneath the foundations of one of the gates, and a slip occurred in the canal dike. Remedial measures were successfully carried out in each case. The largest of the culvert aqueducts (all of which had been built in timber) was not sufficiently strong; it was rebuilt in masonry in 1569 by Georges Rinaldi—a construction said to have been greatly admired by Peter the Great when he travelled on the canal.

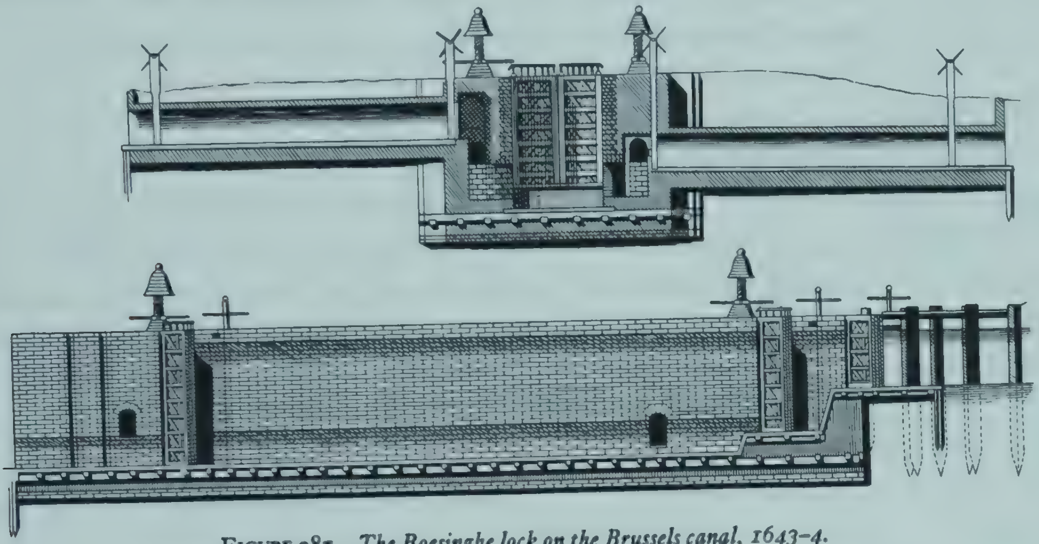

FIGURE 287—*The Boesinghe lock on the Brussels canal, 1643–4.*

The Brussels canal was completed only just before the outbreak of war with Spain. When peace was restored in the early seventeenth century the canal system of Flanders expanded greatly [23]. The more notable works included a 44-mile canal linking Bruges, Passchendaele, Nieuport, and Dunkirk *c* 1622, the enlargement of this canal in 1641–61, and an extension in 1666 to Ostend, where a very fine tide-lock was constructed in 1669. In 1670 Dunkirk was linked to the river Aa, at the mouth of which, before the end of the century, another great tide-lock had been built at Gravelines. By 1692 the old river navigations near Lille had been improved and extended with a canal forming a connexion between the Lys and Scarpe.

The most interesting technical achievement of the period, in Flanders, was the celebrated lock at Boesinghe built by Maître Dubie. In 1643–6 navigation between Ypres and the river Yser was improved by the construction of a lateral canal, 4 miles long, beside the river from Ypres to Boesinghe. From this point navigation continued along the river to its junction with the Yser. The fall in this 4-mile reach amounted to 20 ft and, instead of building three locks of normal dimensions, the whole of the fall was taken in one great lock at Boesinghe (figure 287). This is remarkable not only for its size but for the use of side-ponds, introduced here for the first time, as a means of reducing the loss of water in operating the lock. Each side-pond takes one-third of the water as the lock is being emptied (the remaining third flowing down the canal), and this volume is available when the lock is to be filled again. Ground-sluices were provided.

VII. CANALS IN GERMANY AND SWEDEN

It has been mentioned that in Germany a number of locks were built in the mid-sixteenth century. As early as 1540, at the suggestion of the Elector Joachim II of Brandenburg, plans were drawn up for a canal linking the rivers Havel and Oder. In 1548 he proposed another, more practicable, scheme for linking the river Spree with the Oder upstream of Frankfurt [24]. Work began on this latter canal in 1558, but it appears that considerable difficulties were encountered and eventually by 1563 operations came to a stop. After many political delays new plans were prepared by order of Frederick William the Great Elector, after whom the canal was named. In 1662, under the direction of the Italian engineer Philippe de Chiese, the earthwork was begun, while construction of the locks and bridges was entrusted to Michael Schmidts, a Dutch engineer who had built a new lock in Berlin five years earlier. The Friedrich-Wilhelm canal, completed in 1669, had a total length of 15 miles and was the third summit-level canal to be built in Europe. As with the early Stecknitz canal the summit was supplied by ground-water from the sandy soil through which the upper part of the canal was carried in a cutting. On the eastern side the canal rose from Neuhaus on the Spree for a height of 10 ft in two locks, and from the western end of the summit-level it fell 65 ft to Brieskow on the Oder.

The construction of the Finow canal, the earlier of Joachim II's schemes, was begun in 1605. After an interruption between 1609 and 1617, for lack of funds, it was completed in 1620. The first reach, 8 miles long, was level with the Havel. The canal then descended the valley of the Finow for 17 miles to Liepe, on a short tributary of the Oder, only eleven locks being provided in the fall of 120 ft. This canal proved to be very unsatisfactory, for the Havel was able to flood down it, and owing to lack of maintenance during the Thirty Years War the works fell into complete decay. By the beginning of the eighteenth century scarcely a trace of them existed. The canal was rebuilt between 1744 and 1751 on a different plan, having two locks up from the Havel to a summit-level, a feeder-channel with an intake several miles upstream on this river, and fourteen locks down to Liepe. The system of water-ways in this region of Germany was completed by the Plaue canal, built in 1743–6, from the Elbe to the Plaue lake and hence to the Havel.

In Sweden, when Telford designed the Göta canal (1808–10), providing water-transport between Stockholm and Lake Väner and thence by the river Göta to Göteborg, he was following in broad principle the scheme first put forward nearly 300 years before in 1526 by Gustavus I, another Renaissance prince with an ambition for canals on a grand scale. It was characteristic of these schemes that they were beyond the technical and financial possibilities of their day. Yet the objective was never forgotten, and in 1596 work began on a much smaller project, which, nevertheless, by canalizing the river Eskilstuna between the Hjälmar and Mälar lakes formed the first step of a route between Stockholm and Göteborg [25]. This was completed in 1610, with eleven timber locks built by Petter von Lübeck, with a Dutch engineer acting as consultant. It was not altogether successful, however, and in 1628 surveys were made by Andreas Bureus for a canal linking Lake Hjälmar and the river Arboga which flows into Lake Mälar. This canal was constructed 1629–39 and entirely superseded the older Eskilstuna route. The fall of 75 ft between Arboga and Hjälmar was taken in ten masonry locks. The works, under the direction of Carl Bonde, included a cutting half a mile long in rock. Trade was considerable and before the end of the century the canal had to be enlarged. The Dutch engineer Tilleman de Moll was in charge of these improvements, which were carried out in 1691–1701. The old locks were replaced by eight new ones, each 24 ft wide and 100 ft long with falls of up to 13 ft, and the depth was increased to 8 ft. Meanwhile in 1635 surveys were made of the country west of Lake Vatter along the course of what was later to be the summit of the Göta canal, and as early as 1607 a lateral cut and lock had been built at Lilla Edet on the Göta river. The subsequent stages in the construction of this great waterway linking the Baltic and the North Sea, associated with Polhem, Telford, and Count von Platen, lie outside the scope of the present chapter [26].

VIII. ENGLISH RIVER NAVIGATIONS

In the British Isles the first summit-level canal was built as late as 1737–45, by Thomas Steers, from Newry in Northern Ireland to Lough Neagh, to bring coal from the Tyrone collieries over the canal and thence by sea to Dublin.

Indeed, canal-construction was not undertaken on a large scale until the days of the industrial revolution, though in the preceding 150 years a great deal had been accomplished in extending and improving the river navigations [27]. To give a measure of this progress, it may be mentioned that by the end of the eighteenth century some 2000 miles of navigable water existed in England, of which approximately one-third was in the form of canals built between 1760 and 1800; one-third was in the form of 'open' rivers which were naturally navigable; and the remaining third had been created as a result of the work of engineers, chiefly between about 1600 and 1760.

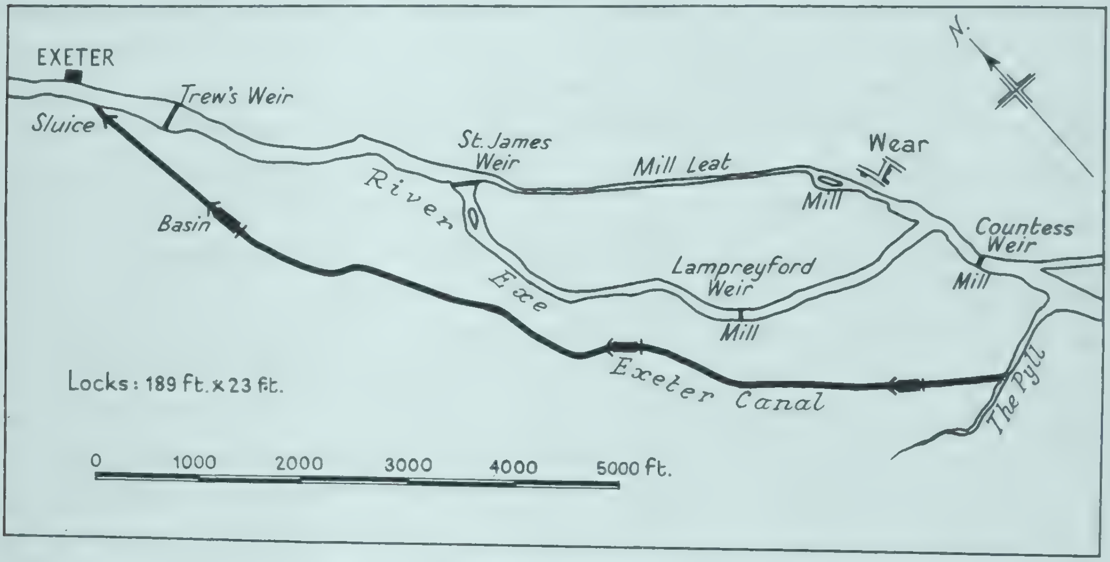

FIGURE 288—*Map of the Exeter canal, 1564–7.*

It will be recalled that during the Middle Ages stanches had been built, usually in mill-weirs. These were works consequent upon the existence of the mills, rather than works designed from the outset to improve navigation. And for small medieval craft navigation was possible on many rivers that would be considered impracticable by modern standards. In the course of time, however, the medieval river system was increasingly felt to be inadequate, and the works at Exeter in 1564–7 (p 451 and figure 288) represent the beginning of a new outlook on water-transport in England.

Shortly afterwards, improvements were undertaken on the Thames and its tributaries. Reference has been made to the lock completed in 1574 on the Lea (p 451), while between 1624 and 1635 three locks were built on the Thames at Iffley, Sandford, and Abingdon. The Wey was made navigable in 1651–3 for a length of 15 miles, with a fall of 86 ft, from Guildford to Weybridge (figure 289).

This work was carried out by Sir Richard Weston (1591–1652) and involved the construction of 7 miles of new cut and ten locks, together with twelve bridges and wharves at Guildford and Weybridge. Seventy years later the Kennet was made navigable from Reading to Newbury. John Hore (*c* 1690–1762) was the engineer for this work, and for the Avon navigation from Bristol to Bath. On the Kennet, between 1718 and 1723, he built $11\frac{1}{2}$ miles of new cuts 54 ft wide, and in the total length of $18\frac{1}{2}$ miles, with a fall of 138 ft, he provided eighteen locks each having a length of 122 ft and a width of 19 ft. In the west country the Severn was the main artery of transport, the river being an open navigation up to Shrewsbury. It was evident that great advantages would be gained by making some of the larger tributaries of the Severn navigable. Work on the Warwick Avon from Tewkesbury upstream for a distance of 32 miles to Bidford was

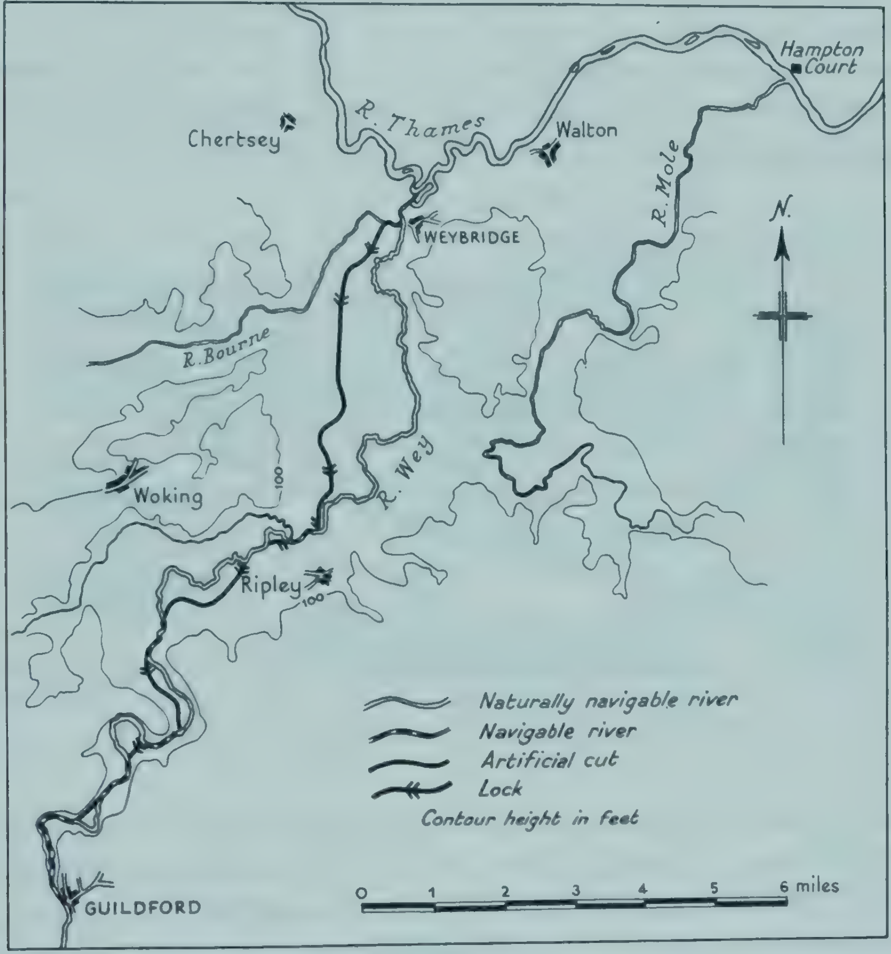

FIGURE 289—*Map of the Wey canal, 1651–3.*

undertaken by William Sandys in 1636–9. This navigation was extended to Stratford-on-Avon in 1675–7 by Andrew Yarranton (1616–84). In 1662 Sandys attempted to make the Wye navigable from Chepstow to Monmouth, but the technical difficulties proved too great. In the same year, however, Yarranton started work on the Worcestershire Stour and brought the navigation up to Stourbridge.

The first engineering works of importance on the rivers of Yorkshire were carried out by John Hadley on the Aire and Calder (1699–1703), from the Ouse up to Leeds and Wakefield (figure 290). Between 1726 and 1729 William Palmer extended the Don navigation up to Sheffield, and he also supervised improvements on the Ouse in 1727–32. Meanwhile, in the north-west, Thomas Steers (1672–1750), who had completed Liverpool's first dock in 1715, made the rivers Mersey and Irwell navigable to Manchester in 1722–5. By 1732, after three years' work, the Weaver navigation was constructed by Thomas Robinson, with eleven locks in a length of 20 miles and a fall of 42 ft from Winsford to the Mersey estuary.

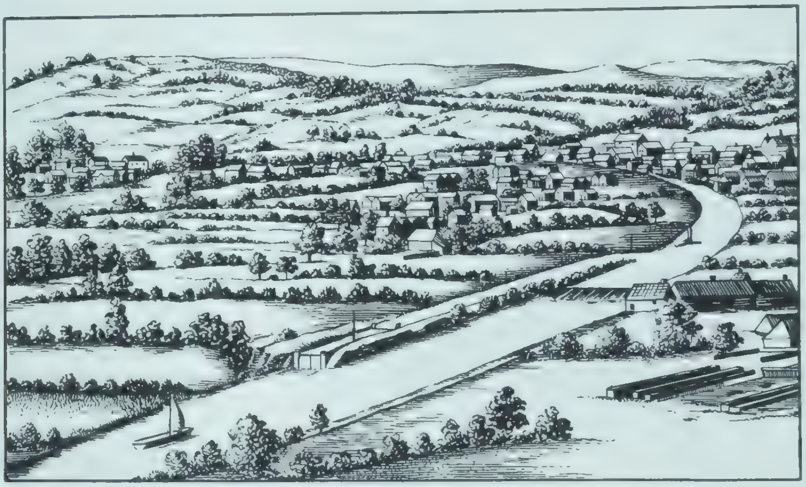

FIGURE 290—*View of a lock on the river Aire Navigation near Leeds*, c *1702.*

This summary of a few of the English river navigations indicates the scope of the works. Their economic importance is shown by the fact that on the Weaver, for example, over 50 000 tons were carried annually in the period 1750–60. Their construction involved weirs, flood-gates, bridges, and wharves as well as locks and, although individually their technical importance cannot be compared with that of the contemporary canals in France, they represent altogether a considerable engineering achievement.

IX. PROJECTS OF THE FRENCH RENAISSANCE

Inland navigation in France followed a pattern in marked contrast to that in England [28]. It is true that some attention was paid to river improvement, but the principal feature of French work in the seventeenth century was the construction of two great summit-level canals which are so important in the history of engineering that they will be considered separately. Indeed the Languedoc canal (1666–81) was the greatest feat of civil engineering in Europe between Roman times and the nineteenth century; it was largely based upon experience gained from the Briare canal, on which work began in 1604.

The Languedoc canal was conceived in the ambitious and imaginative mind of Francis I (r 1515–47) who clearly foresaw great advantages both to trade and to the prestige of his country if an inland waterway could be established between the Mediterranean and the Atlantic. When Francis returned home from Milan in 1516, accompanied by Leonardo da Vinci, they discussed together the means for effecting this notable enterprise of constructing a *canal des deux mers*. Two possible routes were found. That in the south would link the rivers Garonne and Aude (the Languedoc canal or Canal du Midi); the other, in central France, would join the rivers Loire and Saône (the Charolais or Canal du Centre). The latter was economically more attractive but technically more difficult, and the first detailed studies were made for the southern canal. The survey was carried out by Nicolas Bachelier (1485–1572), who reported in 1539 that the best route would be up the Aude to Carcassonne, then by canal by way of Villefranche to the Garonne just above Toulouse (figure 292). This was essentially the route of the Languedoc canal as built 125 years later but, though locks were mentioned, Bachelier produced no working plans.

After twenty years Adam de Crapponne (1526–76) again investigated this route, and made reconnaissance surveys for the Charolais canal. When the Wars of Religion put a stop to public works further progress had to await the peace of 1598. Then, under Henri IV and his great minister the Duc de Sully, bridges and water-supply schemes were started, land-drainage was initiated on a considerable scale, and a re-examination of the southern canal was ordered. Humphrey Bradley, the dike-master of Henri IV, who in 1584 had acted as a consultant on Dover harbour and in 1589 had prepared the earliest comprehensive proposals for draining the Fens (pp 316, 318), was engaged on this task. A little later he was concerned with a scheme for a canal linking the Seine and Saône, the origin of the Canal de Bourgogne.

The three great Renaissance projects, the Languedoc, Charolais, and Bourgogne canals, were all eventually accomplished, but they were beyond the resources of the early seventeenth century and Sully very wisely decided upon a more practical scheme for a canal linking the Loire and Seine. This was an attractive commercial proposition; it presented few serious technical difficulties; and it would form a branch of the Atlantic to Mediterranean waterway, leading to the Seine valley and the capital.

X. THE BRIARE AND ORLEANS CANALS

Initial plans for a canal linking the Loire and Seine were drawn up in 1603 [29]. The small river Trezée was to be made navigable from its junction with the Loire at Briare for a distance of some 10 miles up to the village of Breteau; then a cutting with a maximum depth of 75 ft was to be excavated in the high land between the Trezée and the Loing, and this river rendered navigable for a distance of 24 miles down to Montargis (figure 291). The rivers and the canal at the summit were to have a minimum depth of 4 ft and a width of 40 ft, and it was thought that 48 locks would be required. These were to be 90 ft long and 16 ft wide, with mitre-gates and a fall varying from 3 to 5 ft. Bids for the contract were made in January and again in February 1604, when Hugues Cosnier was appointed contractor.

Cosnier then examined the site in detail, and found several important errors in the original scheme, which must have been no more than a sketch-plan. For, instead of the rivers Trezée and Loing being at the same level at the points where they were to be joined by the canal in the summit cutting, there was a difference in elevation of more than 40 ft. Provision had been made neither for supplying water to the summit, nor to secure the works against damage from floods. Cosnier was therefore compelled to produce a new design. He proposed to follow the valley of the Trezée only 7 miles up from the Loire and then, striking northwards, to take the canal over a plateau, crossing this with a summit-level $3\frac{3}{4}$ miles long, from which the canal would be taken down the steep side of the Loing valley to meet this river at Rogny. The new route was nearly 3 miles shorter than the original scheme, it avoided the deep cutting, and it made possible the supply of water to the summit. Cosnier also proposed to construct a true canal along the whole length from Briare to Montargis, realizing that this would prove far more satisfactory than merely making the rivers Trezée and Loing navigable. At the same time he suggested that the locks be enlarged and built of masonry.

These radical alterations were examined on behalf of the king by Jean Fontaine, who found himself in complete agreement with Cosnier's proposals, and the new design was accepted by the royal council in December 1604. Sully drafted 6000 troops to provide the labour force, and himself inspected the works from time to time; in 1608 Henri IV, accompanied by the queen, paid Cosnier the honour of visiting the site. By 1610 about three-quarters of the work had been completed, but in May of that year the king was assassinated and the canal lost its royal patronage. Work nevertheless continued, but in 1611 Sully was forced to resign from the government and under the new régime a commission was appointed to investigate the state of the canal and the cost of its completion. The commission was headed by the Marquis de Rhoissy, who had with him

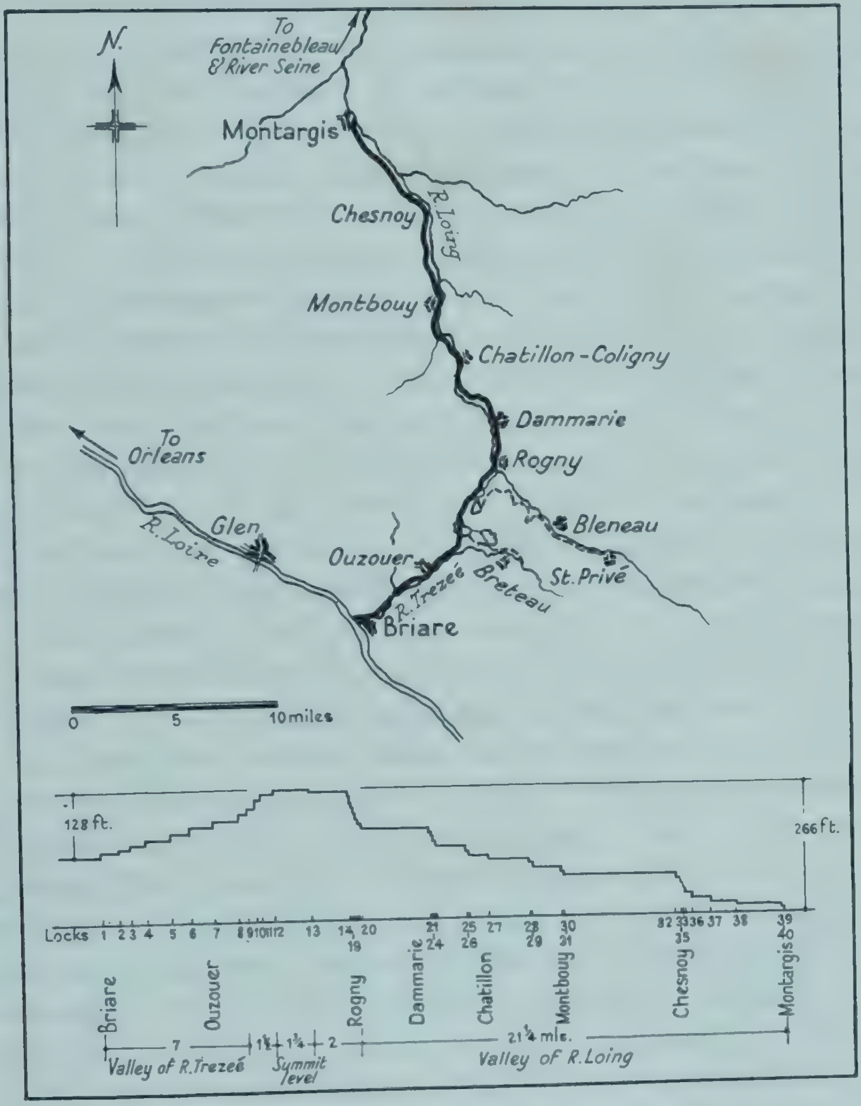

FIGURE 291—*Map and longitudinal section of the Briare canal, 1604–42.*

four experts, including Humphrey Bradley (p 459). A careful survey of the works showed that Cosnier had completed 26 of the required 34 miles and that he had built 35 locks, together with many ancillary works such as 15 discharge-weirs and 9 bridges. The locks had masonry walls 6 ft thick, the distance between the gates was 105 ft, and boats of 15-ft beam could be accommodated. The fall of the locks was usually 10 ft, but in some cases was as great as 14 ft. Cosnier had visited the Brussels canal, and adopted the ground-sluices that he saw in the locks there. These were so efficient that even the locks with a 14-ft fall could be operated in ten minutes. In descending from the plateau to the Loing at Rogny, Cosnier had constructed a 'staircase' of six locks with a total fall of 65 ft, a remarkable achievement for the period. He firmly believed in the principle of providing a series of levels each as long as possible, and to this end he built staircase locks not only at Rogny but also near Dammarie and Chesnoy, as well as a number of double locks. For the summit-supply Cosnier proposed, but had not yet built, a feeder-channel 3¼ miles long with an intake near the head waters of the Trezée running down to a small lake, the Étang de la Gazonne, which acted as a reservoir and from which the water was taken directly into the canal. To provide further storage a lock had been built without a step but capable of impounding the water on one side to a depth of 8 or 9 ft. By this means a length of 1¾ miles of the canal at the summit could act as a reservoir, since the water in this reach could be lowered by 4 or 5 ft without interfering in any way with navigation. At intervals along the canal in the valleys of the Trezée and the Loing a number of intakes from these rivers had also been provided.

Thus between the years 1604 and 1611 Hugues Cosnier had designed and almost completed a summit-level canal, rising 128 ft from the Loire and falling 266 ft to the Loing at Montargis. He had built 35 locks, and had designed the summit-supply as well as looking after the supply of water at other parts of the canal and safeguarding it against floods by means of the discharge-weirs.

All these works are mentioned in the report of the Commission of 1611, in which de Rhoissy wrote '*que ce serait un grand abus de laisser et abandonner une si louable entreprise, qui a esté fort bien entendue, conduite et presque parfaicte.*' Nevertheless, for political and financial reasons the scheme was abandoned. Cosnier made proposals to complete the work partly at his own expense, in return for the right to collect tolls from the canal during the first six years of its operation; but with wars and with the weak government of the Regency nothing was done for seventeen years. During this interval Cosnier naturally was engaged elsewhere, notably in connexion with the Arcueil water-supply to Paris. In 1628 a re-examination of the Briare canal was made by Francini and Le Mercier, who strongly recommended the completion of the work but pointed to the need for additional water-supply at the summit to compensate for the large losses of water involved in operating the six locks at Rogny. For this purpose they proposed a second feeder-channel with an intake on the Loing at St-Privé, leading to a small lake, which would act as a reservoir, at a level just above that of the summit. In order to forward the work to which he had already devoted so much thought and time, Cosnier offered to construct this feeder-channel provided he was paid a part of the money still owed to him since 1611. This offer was accepted, but he was now an elderly man in ill health and he died in the last month of 1629. *Saluons, au passage, la mémoire de ce grand ingénieur!* [30].

Another eight years passed before, in 1638, Guillaume Boutheroue and Jacques Guyon obtained letters patent from Louis XIII to complete the work and to pay the land-compensations still outstanding, in return for ownership of the canal. They formed a company for this purpose and, under the direction of Boutheroue's brother François, the damage of twenty-seven years of neglect was made good, the last five locks down to Montargis were built, and the canal was put into operation in 1642, exactly as conceived by Cosnier. The proposal of 1628 to provide a feeder-channel from St-Privé proved, however, to be well founded, and this channel was duly constructed in 1646. It is notable for having a fall of only $5\frac{1}{2}$ ft in a total length of 13 miles (5 in per mile).

The undertaking was a satisfactory investment and during the latter half of the seventeenth century the company received an annual return of 13 per cent on its capital. The annual trade on the canal in this period was about 200 000 tons. This figure was maintained throughout the eighteenth century, doubled during the nineteenth, and is trebled at the present day.

The goods transported on the Briare canal consisted chiefly of coal and of wine brought down the Allier and the upper Loire to Paris, but part of the trade came up the Loire from Nantes, Tours, and Orleans. To shorten the journey of this latter commerce and to facilitate the export of timber from the forest of Orleans a canal was built in 1682–92 with a length of 46 miles, rising 98 ft from the Loire at Orleans to the summit in 11 timber-locks and descending 132 ft to the Loing at Montargis, in a distance of 18 miles, in 17 locks [31]. The chief technical problem in the Orleans canal was the summit-water supply. The canal crosses an extensive and very flat plateau, and the principal feeder-channel, known as the Rigole de Courpalet, has a length of 20 miles with a fall of only 4 ft ($2\frac{1}{2}$ in per mile). The flow in this channel was therefore very slow, and the system would have been ineffective but for the use of the summit-level as a storage reservoir, in the manner already devised by Cosnier on the Briare. With a length of 11 miles, the summit-level of the Orleans canal had sufficient capacity to store the water flowing from the feeder-channels during the night; this was used to replace the loss of water in operating the canal the following day. The consultant for the Orleans canal was Sébastien Truchet (1657–1729), a well-known *savant hydraulicien* and pupil of the physicist Mariotte [32]. The high degree of accuracy required in surveying the Rigole de Courpalet is remarkable, and calls to mind the achievement of Edward Wright in his survey for the New River water-supply for London as early as 1609 [33]. Here the fall was 18 ft in a length of 39 miles, or 5½ in per mile (almost the same slope as that of the Rigole de St-Privé). The Courpalet feeder is also memorable as having provided a valuable subject for investigation by Antoine Chézy in 1769 during his classic research on flow in rivers and open channels [34].

The Loing between Montargis and the Seine which, after 1692, took the traffic both of the Orleans and the Briare canals, was navigable only by virtue of twenty-six stanches situated in the weirs of the various mills along the river. With the two canals in operation the delays caused by operating these stanches became intolerable, and between 1719 and 1723 a lateral canal alongside the Loing was built by Jean-Baptiste de Règemortes, with twenty-one locks in a length of 32 miles [35]. In 1726 his son Noël rebuilt, in masonry, the locks on the Orleans canal, and thus the canal system between the Loire and Seine was perfected.

XI. THE LANGUEDOC CANAL

It is not surprising that progress was delayed on the Languedoc canal in the south of France since, after the death of Henri IV, the government was reluctant even to complete the Briare canal. It was not until 1662 that the requisite combination of an able administrator in Colbert and an engineer of genius in Pierre-Paul Riquet (1604–80) was found [36]. In the previous year Riquet, with the assistance of François Andreossy (1633–88), had for the first time worked out a scheme for the supply of an adequate amount of water to the summit. For this purpose he proposed a feeder-channel 26 miles long with an intake on the river Sor near Revel. Its flow was to be increased by a second channel taking water from three mountain streams, the Alzau, Vernassonne, and Lampy (figure 292). For the route of the canal, he adopted essentially the line proposed by Bachelier more than a century earlier. The river Lers [now l'Hers] was to be made navigable from Toulouse to a point east of Villefranche (Haute-Garonne). A canal was then to be cut rising over the summit and joining the river Fresquel near Castelnaudary. Below this point the Fresquel would be made navigable to its junction with the

Aude near Carcassonne, and this latter river would in its turn also be made navigable down to its mouth on the Mediterranean coast.

In November 1662 Riquet communicated his ideas to Colbert. Colbert had little difficulty in arousing the interest of Louis XIV, who preferred that even the practical undertakings of his reign should exhibit the quality of grandeur. The king appointed a royal commission to investigate the plans, and during 1663 and 1664 Riquet was busy working out his scheme in more detail, paying visits to Colbert in Paris, and to Hector Boutheroue, the younger brother of François and one of the directors of the Briare canal, who had been appointed as the principal expert on the commission. In November 1664 Riquet presented his plan formally to the commissioners, who called upon the assistance of Andreossy and Jean Cavalier, Geographer Royal, and two other surveyors. During a period of seven weeks the commission made a detailed investigation of the terrain, approving Riquet's plans in general, but proposing that instead of making the rivers Lers, Fresquel, and Aude navigable, a canal be made along the entire length of the route from Toulouse to the Mediterranean. They also proposed that the canal should end not at the mouth of the Aude but in the Étang de Thau, with a port constructed at Sète.

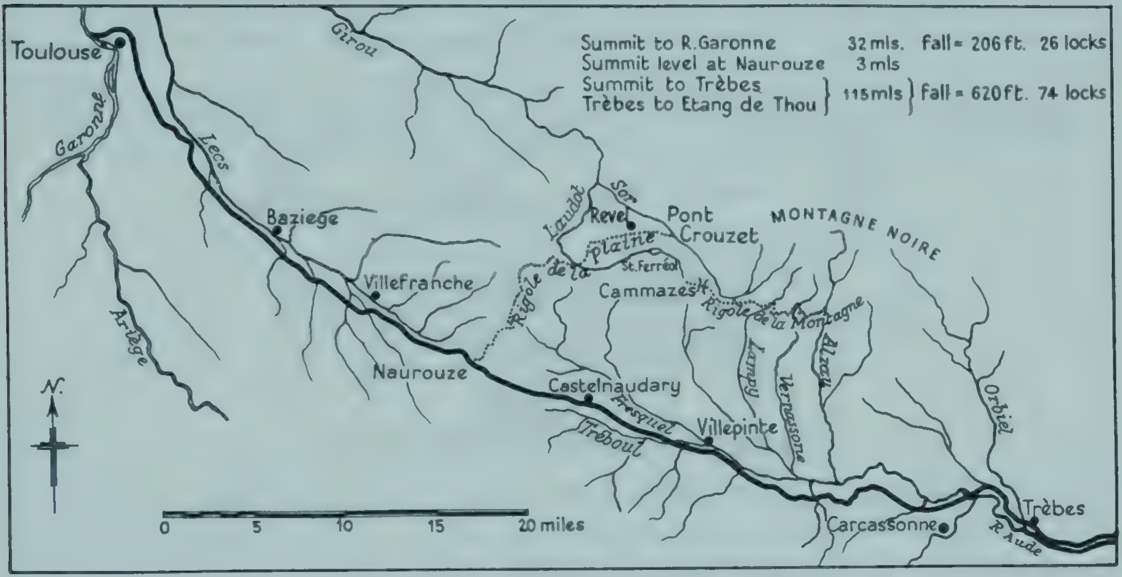

FIGURE 292—*Map of the western part of the Languedoc canal, 1666–81.*

The commission's report was approved by Colbert and the king, but as a practical demonstration of the validity of the plans for the summit-supply it was suggested that a pilot channel be dug from the Sor to the summit at Naurouze. This work was carried out by Riquet between May and October 1665 with complete success. Meanwhile de Clerville, chief royal engineer, prepared the contract documents for the first section of the canal between Toulouse and Trèbes. In October 1666 Riquet was appointed contractor, and by January of the following year 2000 men were employed, a number doubled by March. In 1668 specifications were drawn up for the second part of the canal from Trèbes to the Mediterranean, and in 1669 more than 8000 men were at work. Riquet had established an admirable organization: the canal was divided into twelve sections each under an Inspecteur-Général, one of whom was Andreossy. Under the Inspecteurs there were men with more local responsibilities, each having under his control the requisite number of foremen and labourers. There were also seven surveyors permanently engaged. By 1680 the work was rapidly approaching completion, but in October Riquet died and so was denied the satisfaction of seeing the opening of the canal seven months later, in May 1681. Riquet was succeeded as director of the works by his son Jean-Mathias, under whom the work continued for a number of years: much had still to be done before the canal was perfected in 1692.

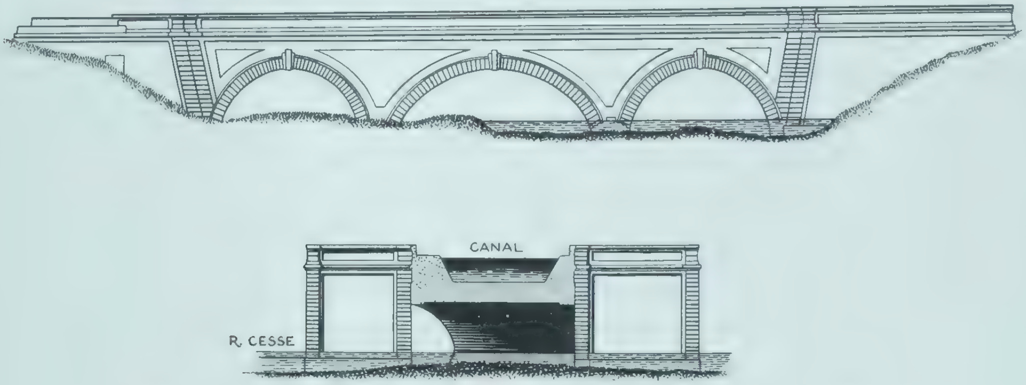

FIGURE 293—*Aqueduct over the river Cesse on the Languedoc canal,* c *1688.*

The Languedoc canal excited the admiration of the world. Travellers came to see it under construction and poets celebrated its engineer, Colbert, and the king. Voltaire, in his *Siècle de Louis XIV*, having mentioned the Louvre, Versailles, and other building works of the *Roi Soleil*, said: '*mais le monument le plus glorieux par son utilité, par sa grandeur, et par ses difficultés, fut ce canal de Languedoc qui joint les deux mers.*' Just as the Briare canal had served as the model for the Languedoc in France, so the Languedoc was the prototype for succeeding great canal undertakings in Europe.

From the Garonne at Toulouse the canal rises 206 ft to the summit, in a length of 32 miles and with 26 locks. The summit-level is 3 miles long, and the canal then descends 620 ft to the Mediterranean, with 74 locks in a distance of 115 miles. The whole canal from Toulouse to the Étang de Thau is therefore 150 miles long, with 100 locks. The contract plans called for a channel 50 ft wide at the water-surface, a depth of 8½ ft, and side-slopes of 1:1. These were too steep, and after several slips had occurred the section was modified to a top width of 64 ft, a depth of 6½ ft, and side-slopes of 2½:1, the original base-width of 32 ft being maintained.

The walls of one of the locks collapsed soon after construction, and to prevent any further trouble of this kind the existing locks were rebuilt and the whole lay-out revised to reduce the height of the walls by one-third, to provide stronger foundations, and to curve the walls in plan, the better to resist the earth-pressure. In their new form, dating from 1670, the locks had a length of 115 ft between the gates, an entrance-width of 21 ft, and an average fall of 8 ft. The oval shape, though of great solidity, leads to a greater loss of water than from the usual rectangular chamber. Many of the locks were grouped together, the most notable examples being near Béziers, where Riquet built a staircase of 8 locks having a fall of 70 ft. At a distance of about 6 miles upstream of these locks the canal passed through the Malpas tunnel, 180 yds long. There were three major aqueducts. One over the river Repudre with a single arch of 30-ft span was built before 1680. The other two over the rivers Orbiel and Cesse (figure 293) were designed in 1686 by the celebrated engineer Sébastien Vauban (1633–1707, p 372) and built by Antoine Niquet (1639–1724). The countless streams crossing the line of the canal were taken under it in culverts (figure 294). Numerous diversion-weirs, spill-ways, and road-bridges were constructed, as well as the new port of Sète.

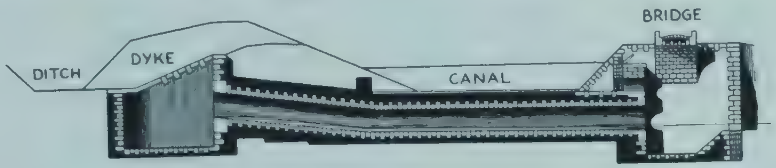

FIGURE 294—*Culvert under the Languedoc canal near Villepinte, c 1680.*

This was civil engineering on a grand scale, but perhaps the chief technical interest lies in the scheme for the summit-water supply. The furthermost intake is on the river Alzau (figure 292), situated high up the southern flanks of the Montagne Noire. From this point a feeder-channel, known as the Rigole de la Montagne, runs for a distance of 12 miles, crossing two other streams; then it divides, one short branch leading to the river Sor and the other continuing for 3 miles and passing through a tunnel at Les Cammazes to supplement the head waters of the Laudot.[1] The Rigole de la Plaine, with an intake on the Sor at Pont Crouzet, flows for 8 miles to meet the Laudot and then, carrying the whole supply in a channel 20 ft wide and 9 ft deep, runs for a further 19 miles to the Naurouze summit of the canal. In the valley of the Laudot, at St-Ferréol, Riquet constructed between 1667 and 1671 a large earthen dam with a masonry core wall, 105 ft in height (figure 295), to form a storage reservoir of 250 million cu ft capacity [37]. During the summer the flow of the Rigole de la Montagne was directed entirely into the Sor, but in the winter the greatly increased flow in this channel was diverted partially into the St-Ferréol reservoir, the water of which could be used during the following summer. This brilliantly conceived plan proved to be wholly satisfactory, and it was not until 1777–81 that a second reservoir was constructed on the Lampy, with a masonry dam 54 ft high, to provide an additional source of water required by a branch canal to Narbonne.

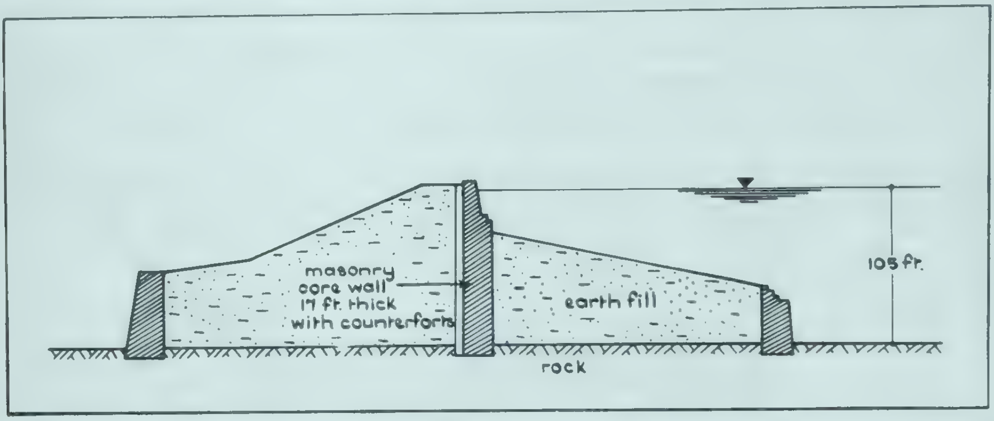

FIGURE 295—*Cross-section at maximum thickness of the St-Ferréol dam, Languedoc canal, built 1667–71. The capacity of the reservoir was 250 million cu ft.*

With the perfection of the Languedoc canal in 1692 civil engineering had reached maturity in this field, and the technical basis had been provided for the vast expansion of the canal system of Europe which took place in the succeeding period of industrial development.

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18

SHIPS AND SHIPBUILDING

G. P. B. NAISH

I. OARED SHIPS

THE state of the development of the ship at the opening of the sixteenth century is of particular interest. By then, the great modern voyages of discovery had started, opening up the sea-lanes of the world for trade and the spread of western civilization among the peoples who came in contact with it through sea traffic. It has been claimed that great improvements in ships enabled these voyages to be made. Is this true? And if so, what were those improvements? These are important questions. Also we are often told that the warship became doubly formidable by the introduction on board of heavy guns. Our own Henry VIII is given credit for this step. Can this view be substantiated? First let us survey very shortly the types of ships trading and fighting in European waters at the beginning of the century.

The Mediterranean war-galley. The oared galley was the traditional warship of the Mediterranean, but at the beginning of the sixteenth century the type had changed considerably from the galley of classical times. A typical galley as built in Mediterranean dockyards was about 120 ft long on deck by 15 ft beam amidships. The warship was lightly built with a framework of keel and ribs covered by planking placed edge to edge, called in the north carvel-built. The deck was only 5 or 6 ft above the keel. From 1290–1540 the popular war-galley was called a trireme. There were 25 to 30 benches a side and three oarsmen sat on each bench, every man pulling a separate oar. The thole-pins were on the same level in groups of three.

The typical galley had a single deck and was divided into three parts; a fighting-platform in the bows and a sterncastle and cabin aft with the intervening rowing-space divided down the middle by a gangway. The sides were extended by outrigger frames to give the oarsmen suitable leverage. Thus in a hull with a maximum beam of 15 ft there was a space 22 ft × 106 ft for the oarsmen. The benches slanted inwards towards the after end of the ship. The oars were each 29 to 32 ft long and weighed 120 lb. About one-third of the length of the oar was inboard, and this was weighted to balance the outboard portion.

There were low steps in front of the benches so that the oarsman mounted, placed the blade of his oar in the water, and leaned back, bracing his feet against the step.

A single light mast forward carried a lateen or 'latin' sail, the typical triangular sail of the Mediterranean (vol II, pp 584, 586). This sail allowed the oarsmen to rest when the galley was cruising in fair winds, but was furled and hoisted out of the way in action. One large and some smaller guns were mounted in the bows, firing forward under the forecastle platform. There was also a long beak-head with a ram or spike above water. The galley was steered by a rudder hung on the stern-post. In action the galley was manœuvred to point at the enemy, the guns were fired, and in the resultant confusion the rowers pulled hard until the spike of the beak-head was rammed into the enemy's upper works, serving as a bridge over which the soldiers were able to board the enemy ship. Unlike the classical galley, the later vessel had no underwater iron ram and its oarsmen were virtually slaves, that is, criminals or prisoners-of-war, not volunteers paid extra wages for their labour. In the wars between Christian and Turk the lot of the galley-slave was unenviable. Yet the officers, sailors, and soldiers (some 50 in all) fared little better than the 150 oarsmen. There was accommodation in the cabin aft for the captain, and his great cabin was used as a mess-room by day. The oarsmen lived on their benches at sea, being controlled by whistle and encouraged in times of stress by extra wine or the lash.

The galley was not eminently seaworthy even within the Mediterranean, and was less so in the Atlantic. Under sail it suffered from the weight of the guns forward and from the effect of the outriggers and oars to leeward. But much was accomplished with the galley fleets, which could be handled in calm weather with the purpose and precision that we associate with the steam navies of today.

There were smaller galleys such as the *fuste*, *galeotte*, *bregantini*, and *frégate* or *fregata*. The names are of interest chiefly from their use again in later times. The war-galleys could also be used to carry light and valuable cargoes and important travellers. There were heavier merchant-galleys designed to carry the rich eastern merchandise which was still brought overland to the Levant and reached western Europe by sea from the eastern Mediterranean.

The Mediterranean trading-galley. In the year 1500 the finest merchant-ships in the world were probably the great trading-galleys, by that date mostly of Venice, which could carry about 250 tons of merchandise below decks (vol II, figure 534). These trading-galleys were built with a length six times their beam, as compared with the eight-to-one ratio of the war-galleys. They had three masts and lateen sails. Indeed, although termed galleys, by 1500 these vessels were rowed only with difficulty, reserving their oars for emergencies or for entering or leaving port. Nevertheless, this arrangement had the advantage of enabling the trading-galleys to run nearer to a time-schedule and so to be more dependable than was possible for ships depending on sail alone. Their oars were arranged trireme-fashion and a trading-galley mustered a crew of 200 oarsmen and gunners. Such galleys carried costly wares, which paid high freights.

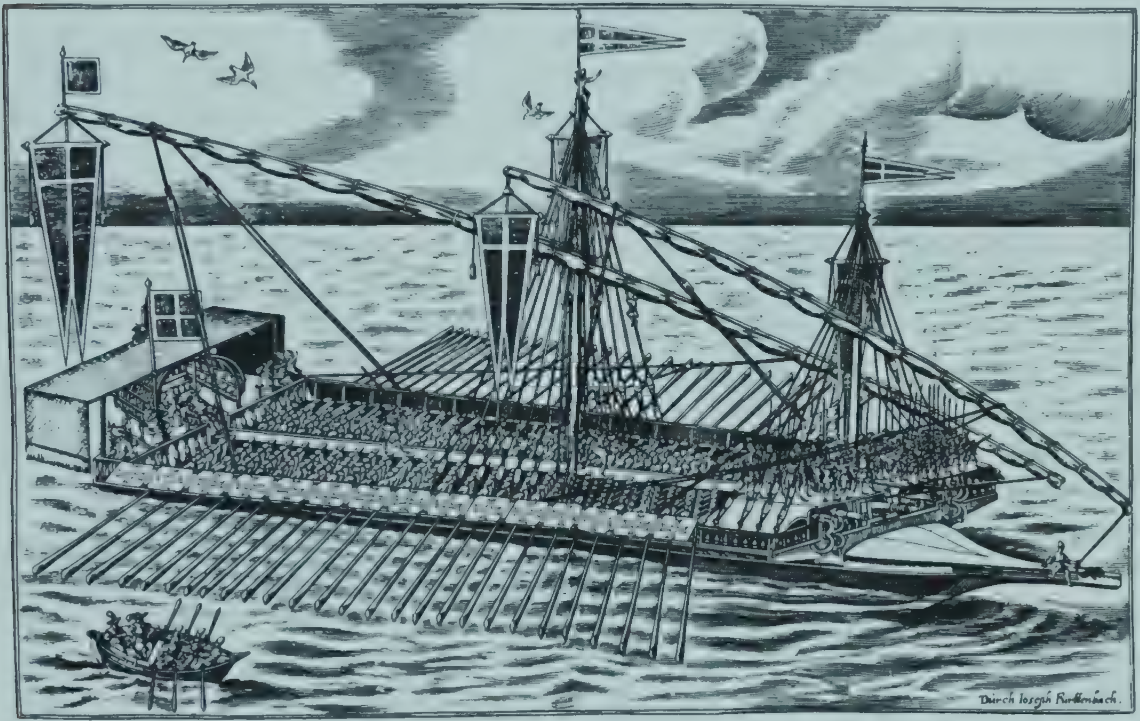
Durch Ioseph Furttenbach.

FIGURE 296—*A Mediterranean galley, a quinquereme with five men pulling at each oar. Guns are carried in the bow. 1629.*

They were powerful vessels and could be defended against pirates, so that some merchants thought it unnecessary to insure goods carried in them.

At the beginning of the sixteenth century the great merchant-galleys from Venice were at the height of their fame, trading to Alexandria and the Holy Land in one direction and Southampton and Bruges in the other. During the second half of the century, however, they gave way to the round ship, but survived for a time as the galleass, the warship under sail and oars which took part in the Lepanto and Armada campaigns.

Why was confidence in the galley diminished at this time? The chaplain who accompanied Sir Richard Guyldforde (1455?–1506) on a pilgrimage to the Holy Land in 1506, sailing from Venice, has left us a journal that enables us to judge the sea-going qualities of these great vessels. For example, his galley preferred to make harbour at night, and in calms or head winds was reduced to anchoring and rolling about at sea. It was not usually rowed, and was incapable of beating to windward. In trying to beat up a strait between two islands the galley was nearly driven ashore when becalmed and wallowing in the swell, and was saved by using oars, obviously regarded as a desperate remedy. A breeze sprang up but the ship was soon almost in the same plight on the other shore. The owners had avoided the cost of the large crew necessary if trained rowers were to be provided, the use of slaves not being practicable in a ship which usually sailed. The improvement in the round ship, that is the sailing-ship, and the rising cost of large crews enforced the abandonment of the galley for general purposes.

In the mid-sixteenth century there was a change in the method of rowing. All the men on a bench tugged at the same oar and a heavy galley could now be propelled much faster. There were sometimes as many as eight men to an oar, but the usual number was five (figure 296). These big galleys were heavily armed but, whether light or heavy, the galley could not now stand the broadside of the sailing-ship. The new full-rigged ship fitted with naval artillery robbed the merchant- and war-galleys of their special advantages, and could keep the sea. Admittedly in 1509 the Venetian trading-galleys, under threat from enemies, had sailed direct from Southampton to Otranto, 2500 miles, in 31 days, but this was regarded as a remarkable feat. Mediterranean powers, however, retained galley fleets throughout the seventeenth century and even into the beginning of the eighteenth. In rowing, the slaves grasped the handles fixed to the loom of the oars, and had to obey orders conveyed by the boatswain's silver whistle. They have their epitaph: 'If there is a hell on earth it is in the galleys where rest is unknown.'

II. THE FULL-RIGGED SHIP

Traditionally the round ship had been the cargo-carrier of the Mediterranean, but, except perhaps in a strong breeze, this merchantman had been no match either in speed or in battle-worthiness for the fighting galley. In the development of the sailing-ship during the Middle Ages there had been interplay between the Mediterranean and northern ideas of build and rig, and the result of the borrowing of ideas had been a levelling-out of traditional differences (vol II, ch 16).

The great achievement of the fifteenth century had been the rapid evolution —indeed, the almost sudden appearance—of the full-rigged ship (vol II, pp 585–8). The sailing-ship in the Atlantic in 1400 had been the one-masted cog with one square-sail (vol II, figure 530). About 1450 the three-masted ship blossomed in both north and south, and by 1500 many ships had four masts and a bowsprit (figure 297). Thus there was a minimum of five working sails on a three-master: the spritsail under the bowsprit; the foresail; the mainsail and its topsail; and the mizzen-sail. This type is most often called a carack or carrack.

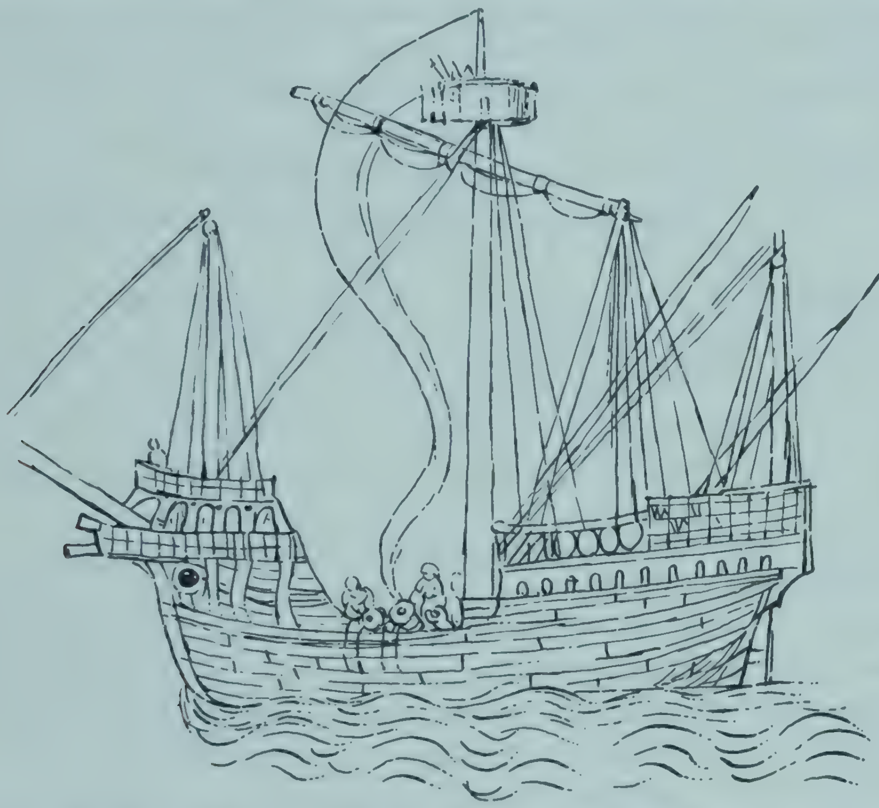

FIGURE 297—*Broadside view of a four-masted ship from the 'Warwick Pageant'—a series of 53 drawings illustrating the life of the Earl of Warwick (1381–1439) probably made between 1485 and 1490. Each of the fifteen large ships shown is of the carrack type, with overhanging forecastles, 3 or 4 masts, and guns firing over the gunwale in the waist. In the figure a short topmast or flagstaff is shown stepped in the topcastle on the mainmast.*

Its hull was distinguished by the aftercastle and poop-deck, and by the forecastle overhanging the stem. In all carracks the after- or mizzen-mast, or, in the case of four-masters, the two mizzen-masts, carried triangular lateen sails, the typical fore-and-aft sail of the south (vol II, figure 536). The mainmast, foremast, and bowsprit set square-sails, the cross-sails of the north. The mainmast and sometimes other masts were in two parts; and the top (originally, it seems, a fighting-top from which to shoot arrows and hurl spears and stones) now carried its own mast and sail.

These ships were carvel-built, in the southern fashion, and had the medial rudder hung from the stern-post developed in the north. During the sixteenth century southern ships preserved certain features that were later abandoned in favour of the northern practice. For example, the ends of the deck-beams protruded through the sides of the ship; the shrouds had no ratlines, and access aloft was by a rope-ladder up the mast. Further progress in the design of the sailing-ship was so slow, especially by comparison with this startling sixteenth-century development, that it is necessary to consider what the ship had gained by multiple masts. The change was probably brought about by the increasing size of ships. Merchants wanted bulkier cargoes carried for greater distances with greater security, and big ships were easier to defend against pirates. They could also carry adequate stores for long voyages. For such ships the single square-sail used in the north was unsuitable. A divided sail-plan was stronger, but for long the mainsail and foresail, the 'courses' or 'corps' as they were called, were much bigger sails than the others. They were the driving-sails, with the topsail as a flying kite. The spritsail and mizzen were found valuable aids to the steering. The ship was manœuvred with a smallish, narrow rudder, and by setting or furling the sails at the ends of the ship the rudder was eased or the ship's head forced round.

It should be noticed that the ship could not sail any closer to the wind with many sails than with the original single square-sail, but sail could be more easily increased or taken off and the ship was handier. Thus the new full-rigged ship was fit for the great voyages of discovery: the hull could hold the people and stores, while the divided sail-plan meant that the ship could be managed more safely off unknown shores and was stronger for a long ocean voyage.

Such long ocean voyages are in fact the impressive achievement of the full-rigged ship. Voyages across the Atlantic, to India, and round the world explain how it was that the Venetian galleys sailed no more up Southampton Water. Trade with the east no longer came to northern Europe by sea from the eastern Mediterranean. Even if the Venetian state had not been ruined by wars on land, its old trade would still have become redundant.

It is uncertain as yet whether the carrack, the new armed full-rigged merchantman, was primarily a northern or a southern type. There is something to be said for calling it an Atlantic type, since many features, especially the greater size which encouraged the improved rig, seem to have come from the ship-wrights around Bayonne, whose work impressed both North Sea and Mediterranean ship-owners. The one-masted square-rigged northern cog had already been copied in the Mediterranean; the lateen mizzen may well have been introduced to the ocean trader from the Portuguese caravels of the type sent by Prince

Henry the Navigator (1394–1460) down the African coast. These little caravels were lateen-rigged on two or three masts and were very suitable for coasting-voyages (vol II, figure 533). They were used for trading and fishing on the coasts of Spain and Portugal, and are often mentioned in the journals of the Elizabethan seamen compiled by Hakluyt. In the second half of the sixteenth century the caravel often carried a square-sail on the foremast. The fore-and-aft rig proved itself more suitable for coasting-voyages and traffic between islands (witness the West Indian schooners of the eighteenth century), while the square rig was more suitable for crossing oceans. For example, in Columbus's voyage in 1492 the *Nina* was a caravel re-rigged at the Grand Canary as a ship. It must be borne in mind that a square-sail, if well set, will point up to windward as close as a fore-and-aft sail.

Official records, such as customs-house returns, prove the general increase in the size of merchant-ships during the fifteenth and sixteenth centuries; the bigger ships during the former century were often out of Spain. From our own Paston letters a correspondent reports in 1458 'sixteen great ships of forecastle' which were Spaniards, and later a correspondent reports the arrival in the Seine of '200 great fore-stages [forecastles] out of Spain'.

By 1500 ships of 600 tons were becoming quite common. Although it is agreed that the development of the full-rigged ship made practicable the voyages of discovery to America and India and the circumnavigation of the world, it must not be supposed that the actual ships in which the great voyages were made were especially fine specimens of the new type. It is well known that Columbus's three vessels were chosen and manned with very little care. In 1518 the five vessels of Magellan's voyage were all bought at Cadiz. 'They are very old and patched', wrote a contemporary, 'and I should be sorry to sail even for the Canaries in them, for their ribs are as soft as butter.' The *Victoria*, the only one of the five that completed the voyage, was a vessel of 85 tons. Little is known about Drake's *Golden Hind* of *c* 100 tons, but she was some 75 ft long over-all by 20 ft beam, and was regarded as a stout vessel by the Spanish captives who reported on her. That Drake could dine off silver plate to music in his own cabin is surprising when one considers that such a small vessel carried some 60 persons. No doubt the new type of ship made long voyages possible, but much human courage and skill were needed too.

To follow the development of the ship, we may consider the navy of Henry VII and VIII, composed of ships of both northern and southern origin.

The full-rigged ship that now held the seas was a combination of Mediterranean and Atlantic shipbuilding practices. Much of the credit for combining the two must go to the ship-wrights of Spain, Portugal, and Brittany. Hulls began to be proportioned on the 'one, two, three' rule of the Spanish caravel, in which traditionally the length of the hull was three times the beam, which in turn was twice the depth. In sailing-ships, unlike galleys, there was no marked difference between the warship and the merchantman, for all ships went armed. Hence the ships that Henry VIII built or bought for his Royal Navy are truly representative of European shipping. He not only employed Italian ship-wrights but obtained ships from Genoa, from Spain, and from the merchants of the Hanseatic league.

Carrack and bark. In 1512 Henry's biggest ship, the *Regent* of 1000 tons, built in 1489 on a French model, armed with 151 iron and 29 brass guns, and manned with 400 soldiers and 300 mariners, grappled the French *Cordelière*, a great carrack of Brest. The French ship caught fire and they blew up together. In Henry's fleet the larger ships, of 800 to 1000 tons, were often called carracks and the lesser, of from 200 to 400 tons, barks. In a contemporary picture of a French carrack two round gun-ports are shown low in the broadside. The other, heavier guns fired over the gunwale in the waist, in the old style.

Henry determined to replace the *Regent* with a larger ship of 1500 tons, called successively while building the *Great Carrack*, the *Imperial Carrack*, and the *Henry Imperial*, and christened or hallowed as the *Henry Grâce à Dieu*, shortened to the *Harry* or the *Great Harry* (plate 21 A). Big ships were a common manifestation of national pride. Henry may have been answering the challenge of the Scottish *Great Michael* of 1506. The *Harry* carried 195 guns and 900 men. One or two of her guns were heavy ordnance. The ship was chiefly armed with 134 serpentines, the common naval cannon; these were small breech-loading guns in which chambers containing the charge of gunpowder were wedged against the breech of the gun. The inventory of the *Harry* shows her to have had four masts, with topmasts and topgallant masts on all save the bonaventure, or after mizzen-mast, which had a topmast only. In 1545 the *Harry* was rebuilt as a smaller ship of 1000 tons, having now a crew of 800 men and 151 guns, 19 of them heavy ordnance with a ball of 60 lb. In 1553 she was accidentally destroyed by fire at Woolwich.

III. HENRY VIII'S ROYAL NAVY, 1546

A pictorial list of 1546 divides the Royal Navy into four categories: ships, galleasses, pinnaces, and barges. There are twenty ships of from 60 to 1000 tons. Although called ships, they are all of carrack type with high castles. Heavy guns fire through gun-ports low in the side. The smallest is the *George*, a four-master of 60 tons.

The fifteen galleasses are drawn without oars, have lower castles, and beak-heads like galleys; their foremasts are stepped farther aft and heavy guns are mounted well up in the bows. They measure from 140 to 450 tons, and the smallest is a three-master. The square transom is a feature of the ships and galleasses. The old-fashioned round stern continued, and in the next century became popular for small merchant-ships called flutes or fly-boats. The ten pinnaces (measuring from 15 to 80 tons) have hulls similar to the galleasses and are three-masters, the fore and mizzen being without tops and the mizzen stepped right aft. The thirteen oared barges of 20 tons each are little galleasses with oars.

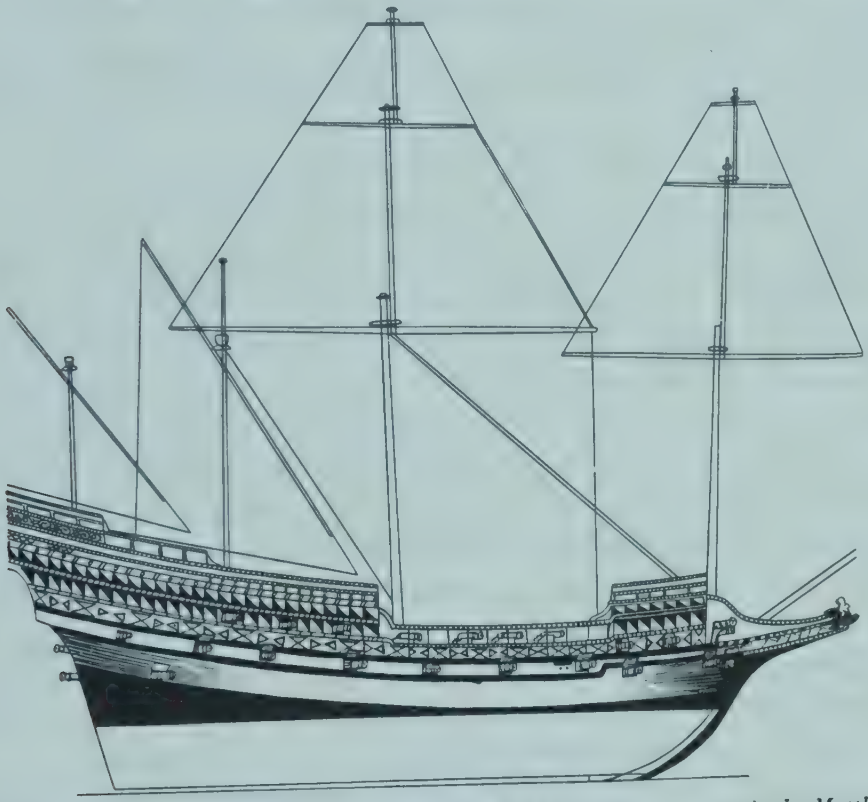

FIGURE 298—*Elevation and sail plan of an English galleon,* c *1586. From a manuscript by Matthew Baker (1530–1613), Master Ship-wright under Elizabeth I.*

The *Subtile* is a typical Mediterranean one-masted galley, fitted out by Venetian ship-wrights. The fifteen ships called galleasses are of a new type, having a galley's beak-head in place of the carrack's overhanging forecastle (plate 21 B). Four of them, the *Antelope*, *Tiger*, *Bull*, and *Hart*, had been built in 1546—as had the thirteen barges. These four represent the latest design for a warship of between 200 and 300 tons. The *Tiger* has a broadside of eight guns, and one or two very heavy guns in the bow firing over the beak-head, as in a galley. The main mizzen-mast has a half-top abaft the masthead, which is also galley-fashion. These four galleasses are flush-decked, in marked contrast to the high-charged carracks. The galley beak-head was a feature of the galleon, an important new type of vessel developed at this time. The so-called galleasses of Henry VIII's navy would thus appear to have been elementary galleons.

The Galleon. The galleon was a type of superior fighting-ship invented by the Portuguese. A large Portuguese galleon, the *São João*, was used in the attack on Tunis in 1535. Contemporary pictures show a four-masted sailing-ship, without oars, mounting a broadside armament and having a galley's beak-head. This beak-head could not be used for ramming because of the bowsprit, which was lashed down to it.

In the second half of the sixteenth century both the Spanish and the English were building powerful men-of-war of this new type, rigged in the same way as the big sailing-ships of the period, but with the hulls longer in proportion to their beam and with lower castles fore and aft. We are told that the galleon had a keel-length of three times the beam, as compared with the old-fashioned twice or two-and-a-half times the beam of the round ship (figure 298).

The galleon was one of the first sailing-ships to be regarded primarily as a warship. She carried her main armament of heavy guns on a gun-deck, firing them through gun-ports in the sides. This gun-deck was not suitable for a merchant-ship, as it interfered with cargo space. Her length and reduction in top hamper made the galleon fast and more weatherly than the carrack. She was described as race-built, while the older ships were known as high-charged. Not all fighting seamen welcomed the galleon, for ships were still carried by hand-to-hand fighting and the castles of a high-charged ship, bristling with small guns, were defended against boarders as castles were defended ashore.

In the Spanish Armada campaign of 1588 there were galleons on both sides. When the Armada sailed from Lisbon it contained 101 vessels of 150 tons and over; the warships included two squadrons of galleons, four Mediterranean galleasses, and four galleys. The galleys were driven into port by stress of weather, and the galleasses proved no match for the English warships. Among the twenty galleons of different sizes were those of Portugal under the Duke of Medina Sidonia and those of Castile under Diego Flores de Valdés. The latter were the galleons of the Indian guard, whose usual service was to protect the treasure-fleets. The *San Martin* and *San Juan* measured 1000 tons and the *Florence* 951, whereas the smallest were of 250 and 350 tons. The dimensions of the larger galleons would have been about 160 ft long over-all, 120 ft on the keel, and 40 ft beam.

An English galleon was the *Ark Royal*, the flagship of the Lord High Admiral, who esteemed her highly and thought her 'the odd ship in the world for all conditions'. Under construction for Sir Walter Ralegh when bought into the Royal Navy in 1587, she was of 800 tons and carried 44 guns. Her ship's company of 425 comprised 300 fighting seamen and 125 soldiers. For comparison, the Spanish *San Martin* had 177 seamen, who were not expected to fight, and 300 soldiers. The *Ark Royal*'s guns included 4 cannon, firing 42-lb balls, and 4 demi-cannon, shooting 30-lb balls. There were 12 culverins (18-pounders), 12 demi-culverins, and 6 sakers (6 lb). The *Ark Royal* was a four-master, with a main topgallant mast (although the inventory of 1588 mentions only the sail). The mainsail and foresail each had two bonnets and a drabbler, which were additions laced on to the body of the sail or course. The main-mizzen and bonaventure-mizzen had two bonnets each. The main tie, that is, the rope hoisting the mainyard, was 40 fathoms of 8½-in rope; the main brace was 70 fathoms of 3-in. The martinets (p 486), for furling the mainsail, were of 1-in rope. The ship carried three bower-anchors weighing 20 cwt each, and a sheet-anchor weighing 22 cwt. She had nine anchor-cables of 17- and 15-in circumference.

The hull was sheathed below water against the ravages of the ship-worm (*Teredo navalis*), probably with elm boards ½-in thick over layers of Stockholm tar and hair of equal thickness. The boards were then nailed in place with broad-headed nails driven in close together. This was the most approved English fashion. The *Ark Royal* sailed no closer than six points off the wind and probably made good seven points.

The average size of the English hired merchant-ships serving against the Armada was 200 tons. The big trading-vessel was still of the high-charged carrack type, an example being the Portuguese *Madre de Dios* captured by the English and brought into Dartmouth in 1592. She was of 1600 tons, carried 900 tons of merchandise, and had a crew of 600 or 700. We are told that at sea her helm required the labour of 12 or 14 men at once in the steerage. When measured by Robert Adams (1540–95), a 'surveyor of the Queen's buildings', she was found to be 165 ft long over-all, 100 ft on the keel, and 46 ft 10 inches in beam. She drew 31 ft of water when fully laden, but only 26 ft when she entered Dartmouth. Her mainmast was 121 ft high and 10 ft 7 inches in circumference at the deck. Her mainyard was 106 ft long. Her captors admired 'the hugeness of the whole, far beyond the mould of the biggest shipping used among us either for war or receipt'.

The spritsail-topmast. In 1600 the English East India Company chartered four merchant-ships for the Company's first eastern venture. Ships of 600 and 300 tons were chosen, and their inventories show a sudden development in the rigging of ships. Unlike ships of the same size that fought the Spanish Armada, they were all three-masters and carried at the end of the bowsprit the little mast, the spritsail-topmast, and its sail which make the ships of this century so easy to recognize in pictures.

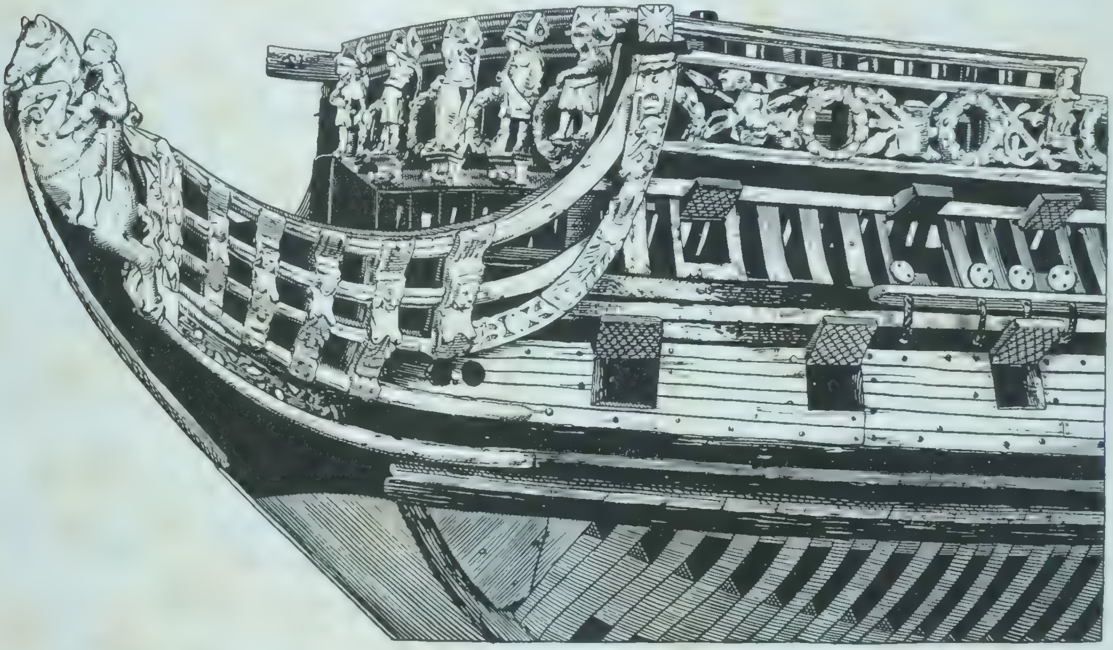

FIGURE 299—*Head of a scale model of an English 90-gun ship, c 1670, perhaps by the ship-wright Sir Anthony Deane (1638?–1721). These earlier ship models were unplanked, but reproduce the beautiful decoration of the period in miniature. The figurehead is a man on horseback. The head-rails, connected by brackets, sweep up to the cat-heads. Five full-length human figures decorate the beak-head bulkhead. The circular gun-ports under the forecastle are surrounded by carved wreaths joined by a painted frieze.*

IV. THE SHIP IN THE SEVENTEENTH CENTURY

The evidence for tracing the development of the ship now becomes much fuller. There are many pictures by good artists, mostly Dutch or Flemish (plates 22, 23). Manuscript sources are more numerous and detailed; good textbooks and nautical dictionaries were published. Sheer-draughts and other plans are elucidated by the fine scale-models which were made in great numbers towards the end of the century, not least by English ship-wrights (figure 299, plate 24 A, B). The new interest in mathematics and science led to attempts to improve the design and build of ships, as well as the sail- and rigging-plan. During this century warships were being built steadily larger, in order to be able to carry more guns. Merchant-ships did not follow this example, 200 tons remaining a general average for ocean-going ships in most trades; yet the great companies, such as the East India Companies of England, Holland, and France, employed larger ships of up to 600 tons or even more.

The galleon type of hull prevailed with a greater length-to-beam ratio than formerly, and low fore- and after-castles. The fore-part of the forecastle ended in a square bulkhead beyond which extended the beak-head, formed by the curved stem and cut-water protruding forwards and finished by the figurehead, with the head-rails on either side (figures 299, 304). It was usual to lay the decks in three sections at different levels, separated by bulkheads under the breaks of the fore- and after-castles. This arrangement allowed more headroom for cabins fore and aft, but the breaks or steps in the decks weakened the hull and it became more and more the custom to have flush decks running from end to end of the ship without break or step. However, in small ships which were more strongly built such breaks to improve accommodation below decks were retained. Reduction of the after-castles made the ships labour less in a sea-way, and it became possible to let in light and air to the officers' accommodation in the stern by fitting stern and quarter galleries and stern windows.

The hulls were strengthened along the sides by the wales, thicker planks running longitudinally, especially at the water-line. Even thicker planks, the chain-wales, were fitted at intervals higher in the side of the hull, and were used to spread the standing rigging, that is, the shrouds and backstays supporting the masts. This standing rigging was set up with dead-eyes and lanyards. The lower dead-eyes were fastened to the chain-wales or channels by means of chains or plates fastened to the hull below. The dead-eye was a round wooden block, with a strop or eye round it and with three holes for the lanyard. Naturally the setting up of the shrouds when the rope had stretched or shrunk was very important to ensure the safety of the masts. Shrouds were being set up with dead-eyes and chains from the first half of the sixteenth century. The masts were set up in three pieces, the lower masts, topmasts, and topgallant masts, and were held together by the tops, trestle-trees, and caps. The forestay and other stays between the masts held them from raking aft. Ratlines up the shrouds made ladders up which the men climbed aloft.

The heavy work of the ship—getting a topmast on end, a gun or the longboat on deck, or weighing the anchor—was done by means of a capstan, a vertical spindle passing through the decks and carrying a barrel or barrels hove round by men pushing capstan-bars fitting into sockets (figure 305). Smaller ships used windlasses, in which case the spindle was fitted athwartships in the bows. The cat-head was a timber sticking out over the bows with sheave-holes in it (figure 299);

through these a tackle was rove and the cat-block at the other end of this tackle carried a great iron hook which was fitted to the anchor ring. A second timber was temporarily rigged out from the forecastle when required, and was called the fish-davit; this was used to hoist and secure the flukes of the anchor, when it was said to be catted and fished.

Wooden ships strained and leaked, especially when old, and rain-water penetrated the decks. Hence pumps were very important. Chain-pumps were fitted to larger ships and the common hand-pumps supplemented the chain-pumps. At the end of the sixteenth century hammocks,[1] first seen by sailors in Brazil, were introduced on board ship. The cook-room was in the hold on a bed of brickwork, and as work had to be done by candle-light the danger of fire was considerable. It therefore became increasingly common to locate the galley (as it was later called) under the forecastle before the belfry (figure 300). Ship's time had long been regulated by a bell, and during the seventeenth century the usual position of this bell in important ships was transferred from the break of the poop or after-deck to the break of the forecastle. The large ship was steered below decks by means of the helm or tiller, a wooden beam socketed into the rudder-head. This was controlled by tackles attached to the sides of the ship. In fine weather the whip-staff was used. It was attached to the end of the tiller and passed through the deck above, leading through the rowel, which was a wooden bull's-eye fitted across a hole in the deck in trunnions allowing it to swing. The helmsman standing on a platform could get a glimpse of the deck and sails through a skylight ('hatch') above his head. He grasped the whip-staff and by

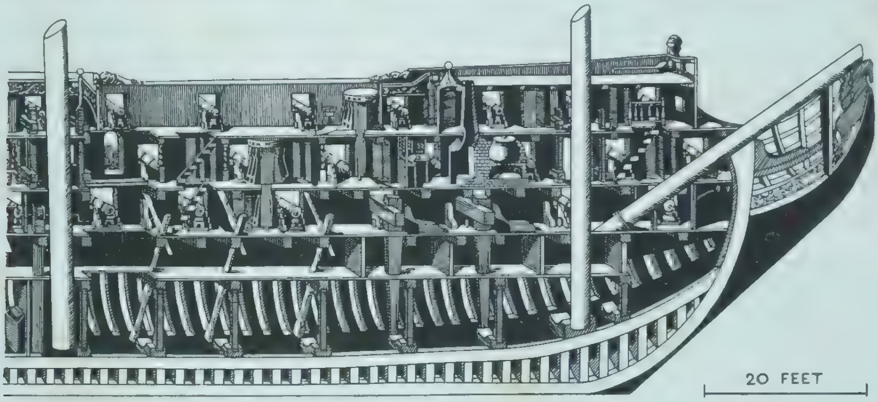

FIGURE 300—*Fore part of a longitudinal section of a first-rate ship, drawn by Edmund Dummer, Surveyor to the Navy 1692–8, showing the gun-decks, the orlop deck, and the hold below. Under the forecastle are the galley-stove and cook-room. The riding-bitts to which the anchor-cables were attached are on the lower gun-deck beneath the galley.*

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[1] Spanish *hamaca*, a Carib word.

pushing it from side to side could work the tiller below, which naturally moved in the opposite sense. In front of the helmsman was the bittacle or binnacle, the box that held the compass and the sand-glass that timed the watch or 'trick' at the helm.

There was little difference in the rig of ships of different nationalities, but very noticeable differences in the style of hull-form and decoration became more pronounced as the century progressed. For example, Dutch ships in order to reach Amsterdam must pass over the shallow and dangerous waters of the Zuider Zee; thus large Dutch vessels were shallower and broader of beam than English and French ships. This is made very clear by a stern view of a Dutch ship. The small merchant-ships of the different countries were very similar. A common type, called a pink, had a broad apple-shaped stern where the planking was worked round to fit the stern-post, and, above, a small square flat transom with stern windows. These pinks were very roomy for their small size.

At the beginning of the century some big ships were still given four masts; one such was the *Royal Prince* of 1200 tons, built by Phineas Pett at Deptford in 1610. A painting, however, shows that she carried a square topsail over both the main- and bonaventure-mizzen sails, which were lateen sails (plate 22). In 1637 the *Sovereign of the Seas* (plate 23, and see p 486), a great ship of 1522 tons built by Peter Pett at Woolwich, had three masts, with topmasts and topgallant masts on all three, topgallant-royal, or royal, masts on the fore and main, and flag-poles above on all three. If not invented by the poets, the names of these new masts were certainly thought poetical. A poet sang of this same *Sovereign*:

> Whose brave Top top-top Royal nothing bars,
> By day to brush the Sun, by night the Stars.

The smaller ships quickly followed the fashion set by the greater, and ships generally, though with only three masts instead of four, gained a great quantity of running rigging to control the more divided sail-plan.

A square-sail was made of lengths of canvas sewn together with the seams vertical. It was roped all round, and rope eyelets or cringles were worked into the corners and other places where ropes must be attached to the canvas. The sail was made fast to the yard by seizings called rope-bands or robins. The yard was hoisted by a halyard, held to the mast by a truss and parrel; its angle to the wind was controlled by brace and lift. The lower corners of the sail were held by sheets, and the courses had both tacks and sheets, the tacks being tapered ropes leading forward while the sheets led aft (figure 306). The sails were furled by men going aloft and tying them down close to the yard, but as a preliminary they were clewed up by clew-lines attached to the lower corners (clews) of the sails, and further gathered up by the leech-lines, running to the leeches or outer edges, and the bunt-lines going to the bunt or belly of the sail. At the beginning of the century ropes called martinets were fitted to the leeches, but the way in which this was done is not quite clear. When sailing close-hauled the weather leech, that is, the leading-edge of the sail, was pulled taut by the bow-line. The square-sail is not necessarily an inefficient one under which to work a ship to windward.

From the middle of the seventeenth century the sail-area of ships was increased by triangular fore-and-aft sails set on the stays between the masts. These were called stay-sails. The area of the square-sails was increased in fair winds by the addition of extensions called studding- or stun-sails. During the first half of the century bonnets and drabblers began to be replaced by a system of reducing sail by reefing. Bonnets were attached to the bottom or foot of a sail; when reefing, the top or head of the sail was gathered up and a strip was tied to the yard by the reef-points, which were lengths of line fitted across the head of the sail at the depth of the reef required. To tie down a reef, men had to climb out along the yard, often in heavy weather, and foot-ropes began to be fitted under the yards as a convenience. The picture of the *Royal Prince* at Flushing, painted in 1623 by Vroom (plate 22), shows reef-points in the spritsail-rigged boats or yachts. Although the rigging of a ship was becoming more complex, this fact is apparently belied by contemporary pictures. The complicated system of crowfeet was largely abandoned; this was a method by which a stay was set up to a mast or another stay by an elaborate arrangement of multiple tackles. These clumsy devices disappear from English ships after the Restoration, which suggests that the cogitations of the Royal Society and kindred bodies had some effect on the thoughts of the humble sailor or shipwright devising a new sail-plan.

Three-masted ships, large or small, were rigged very much alike and seem to have developed together, with the larger ships slightly in the lead. In fact, it is probably fair to claim that in England the *Sovereign of the Seas*, notorious because the ship-money collected to build her helped to lose for Charles I his kingdom and his head, was a great help to the country's mercantile interests by teaching improved ship-wrightery. The same effect probably resulted from the building of large ships by the state in other countries.

V. SHIPBUILDING

Early shipyards consisted of little more than a storehouse erected on a plot of firm ground near, and with access to, a river or other sheltered water of sufficient depth at high tide to float the vessel to be built. Ships were commonly built as near as possible to the supply of timber and also as far as possible from the open sea, to obtain shelter both from gales and from enemy fleets. The preparations for building the *Henry Grâce à Dieu* (plate 21 A) at Woolwich in 1512 are probably typical of the building of a big royal ship anywhere in Europe. Houses, ground, and a wharf were leased, and ship-wrights and mariners were brought to Woolwich from different parts of the country, as were bakers and brewers and quantities of provisions. 1987 tons of timber, mostly from Essex and Kent, were given to the king by dignitaries of the church and state to build the ship, with its great-, cock-, and jolly-boats, and three galleys. Ship-wrights, carpenters, and sawyers were sent out to work in the woods. Blacksmiths set up forges to make the nails, spikes, chains, and bolts. Cables, hawsers, ropes, ratlines, marlines, and caulking also had to be prepared. The workmen were housed and bedded, and one Robert Bregandyne presided over all, with a house and office. Watchmen were placed on guard over the stores, which now included pitch, tar, and rosin.

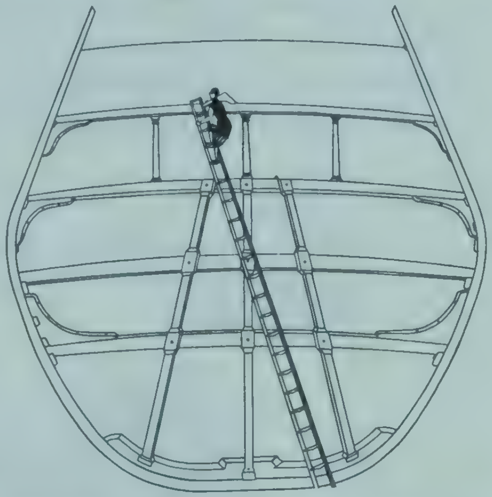

FIGURE 301—*Mid-ship section of a galleon, c 1586, from Matthew Baker's manuscript, showing the 'tumble home' or narrowing of the ship's breadth above the water-line. The figure shows frame-timbers, deck-beams, lodging knees, and struts.*

Then the planks began to arrive and the masts were made, as well as the blocks and parrels, or wooden beads through which were threaded the ropes holding the spars close to the masts. Much money was paid 'for sundry colours, for painting of tops, sails, and images on the *Harry Grâce à Dieu*'. Some of this material arrived in carts and the rest was landed at the wharf from lighters. Hoys, crayers,[1] and other coasters brought guns, anchors, and spars from as far away as Dartmouth, Southampton, and Rye. Thomas Spert, the ship's captain, supervised the mariners who were making the sails and rigging the ships and the three galleys. These galleys were constructed from spare material, left over from building the large ship, which would otherwise have been wasted.

Robert Bregandyne, 'clerk of the King's ships', is believed to have designed the *Henry Grâce à Dieu*, but unfortunately his plans have disappeared. Shipwrights were not alone in making a mystery of their trade and handing down from father to son the secrets of designing and building ships. The first comprehensive textbooks on shipbuilding began to be published at the end of the seventeenth century. In designing a wooden ship the nature of the timber, mostly oak, had to be considered. The planking, perhaps 6 in thick, had to be worked and bent round the bow and stern. The upright timbers had to be built up, the standing, hanging, and lodging knees made from parts of the tree chosen so that the grain of the wood ran with the shape required (figure 301). Once the length of the tread of the keel of a new ship had been decided upon, and the rake of the stem- and stern-post determined (that is, the angle fore and aft at which these two posts should lean or rake), then the shape of the hull depended chiefly upon the drawing of the mid-ship section. To make this drawing, a number of suitable sweeps or arcs of circles were drawn from different centres and the different curves were reconciled with lines joining them up (figures 302, 303).

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[1] Small trading-vessels.

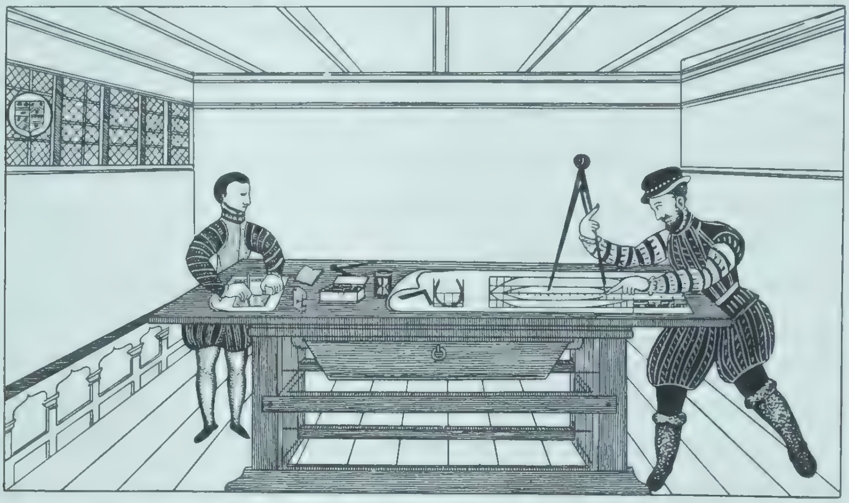

FIGURE 302—*Drawing-office with Tudor ship-wrights at work designing a new ship. The man on the right is measuring with a large pair of compasses preparatory to drawing the long curves which give the shape of the ship's hull. From Matthew Baker's manuscript,* c *1586.*

The ship-wright's art in the sixteenth century and later lay chiefly in not departing too drastically from the secret and proved mid-ship section of some tried and successful vessel built by the same master ship-wright, his firm, or his family. Few calculations were made, and Samuel Pepys (1633–1703) tells us that his friend Sir Anthony Deane (1638?–1721) was the first naval architect to be able to foretell, from working out the weight of material built into a ship and her volume, the draught of water required to float her ready for launching. To avoid disaster, therefore, one ship was built much like another and the develop-

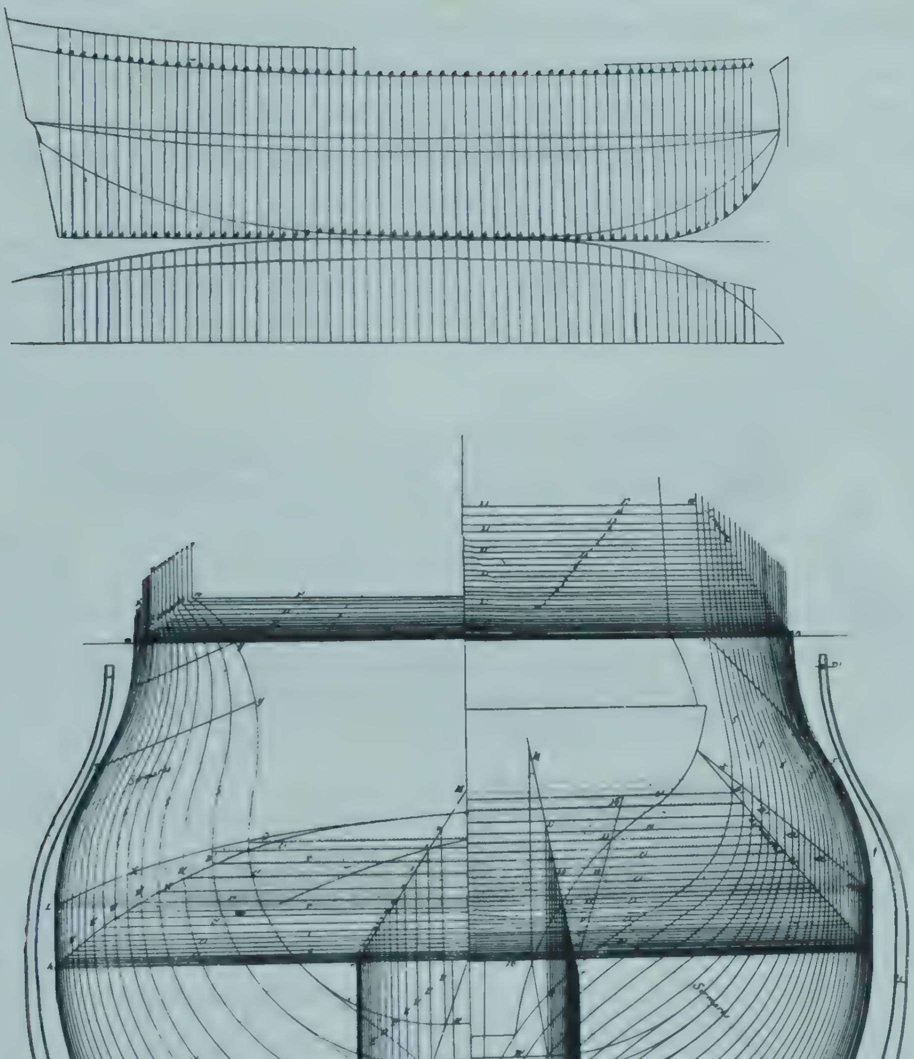

FIGURE 303—*Sections for laying down on the floor of the mould-loft. This had a spacious floor, very smooth and even and well lit, which was large enough to contain the curves of the ship's timbers drawn upon it with large compasses called sweeps. The figure represents every timber from stem to stern of a ship of 1000 tons drawn to scale (¼-in to 1 ft in the original). These curves would be transferred full-size to the floor of the mould-loft. 1711.*

ment of hull-design was consequently very slow. Fortunately, the nature of the timber was such that the hull of a ship was inevitably built streamlined below the water. Once the mid-ship section was decided upon, the fair curves of the hull were drawn and reconciled with the help of a wooden spline, taken at various heights above and parallel to the keel and arranged between the three stations of the rabbet of the stem-post, the chosen place on the mid-ship section, and the rabbet of the stern-post.

When the designer was satisfied with the lines, then the other sections at the proper distances from the mid-ship section could be plotted and drawn. Then a table of offsets seems to have been drawn up, which enabled the sections to be drawn full-size on the mould-loft floor, so that the ship's timbers could be cut according to moulds made from these drawings (figure 303). It will be noticed that wooden ships were designed inside the planking, as the shape of the hull depended on the correct cutting and shaping of the frame-timbers, which were attached across the keel and formed the framework to which the planking was nailed.

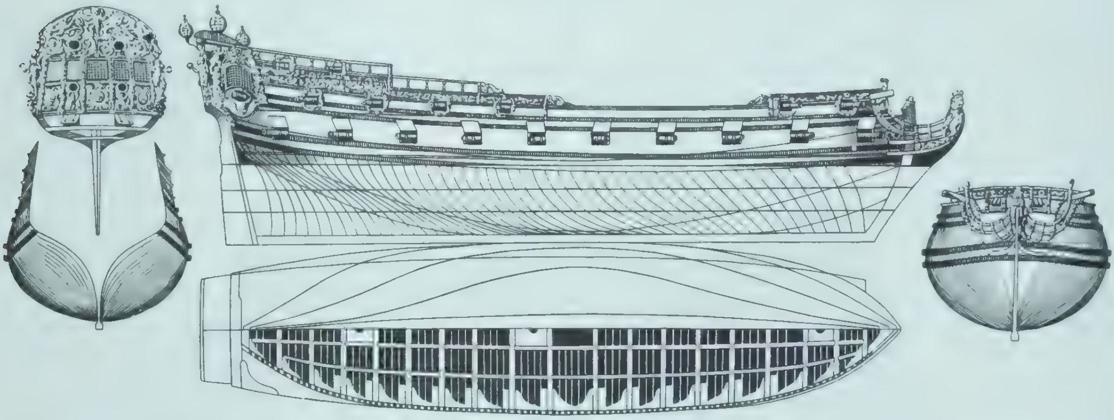

FIGURE 304—*A fifth-rate ship 'of y^e^ largest Dimensions', from a drawing by William Keltridge in a book of plans (1684). Division of naval vessels into 'rates' was introduced by Samuel Pepys (1633–1703).*

From the sheer-draught and body-plan (figures 304, 305) a model was probably constructed with the framework carefully made to scale, which in England was generally ¼-in to 1 ft. The model not only showed the prospective owners what their ship was going to look like, but recorded the decoration agreed, the distribution of gun-ports, and the placing of capstan, cat-heads, and other fittings (figure 299, plate 29 A, B). From before 1700 more models than draughts of ships have survived; these models have not been altered and must therefore be fair copies of draughts, or perhaps rather of the tables of offsets from which ships were built. The offsets were in turn worked out from rough draughts only to be understood by the ship-wrights, who wished to keep secret the exact dimensions of the ships they built.

Models were made of new buildings on shore from very early times. Model ships for the same purpose are frequently mentioned after 1600, and many survive, especially those of English warships after 1650. In view of the lack of scholarship usual among contemporary ship-wrights, it was probably very necessary to see a model before ordering a new ship. In 1668 John Evelyn (1620–1706) witnessed the launch at Deptford of the *Charles*, 'built by old Shish, a plain honest carpenter, master builder of this dock, but one who can give very

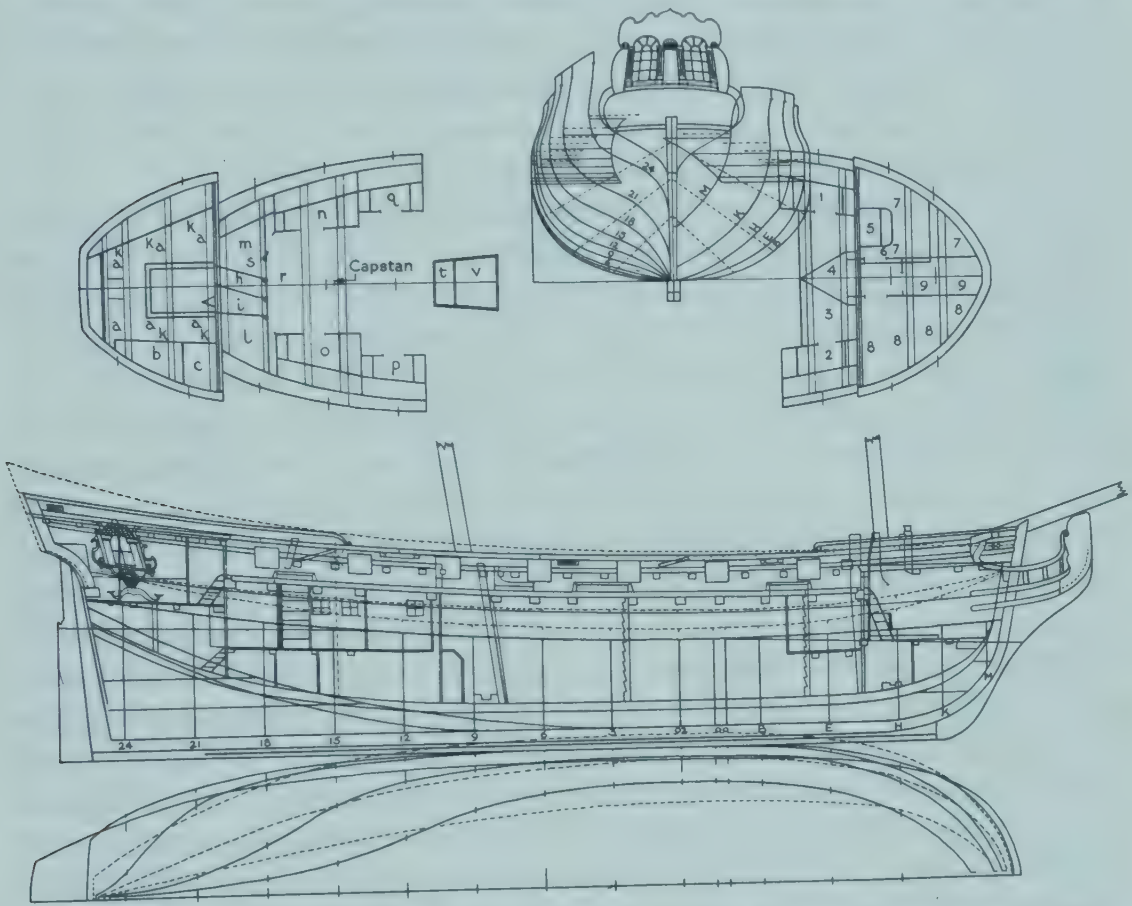

FIGURE 305—*Manuscript draught of the* Shark *sloop, built at Portsmouth in 1732. She was evidently rigged as a brigantine with two masts, that is, like a ship without a mizzen-mast. Often a mizzen-mast was added to a brigantine later. At this time the plans of a ship were commonly drawn on a single sheet of paper. Here are seen a profile of inboard and outboard works, half-breadth plans, body plans, and accommodation plans.* Aft; (a) *great cabin;* (b) *bed-place;* (c) *clerk's office;* (k) *bread-room below cabin;* (l) *carpenter's store-room;* (m) *steward's room;* (n, o, p, q) *cabins of the surgeons, lieutenants, gunners, and the master;* (r) *sail-room and* (s) *fish-room below the platform;* (t) *shot-lockers;* (v) *well.* Forward; (1) *boatswains;* (2) *carpenters;* (3) *paymaster;* (4) *passage;* (5) *fireplace and* (6) *stone hearth;* (7, 8, 9) *boatswains', carpenters', and gunners' store-rooms under the forecastle and fireplace.*

little account of his art by discourse, and is hardly capable of reading, yet of great ability in his calling. The family have been ship carpenters in this yard above 300 years.' The French Admiral de Tourville (1642–1701) noted with approval that in seventeenth-century England ship-wrights were accustomed to make models of ships before they were built. Ship-wrights of other countries, too, made models to show a ship's construction, and sometimes models of an existing ship that had become famous. Fortunately many of these models have been preserved and can be seen in museums.

In the sixteenth and seventeenth centuries most ships seem to have been built in docks. These were constructed partly by digging, partly by building up a wall with stakes and stonework. At low tide the dock-gates could be closed and if necessary the dock pumped dry. When newly built or repaired, a ship could be floated out of the dock on a high-water spring tide. The keel of a new ship was laid on blocks in a dry dock and the stem-post and stern-post were erected and scarfed on to the keel at either end. This was the heaviest work. Then the floor timbers were laid across the keel; the keelson was laid along the keel on top of the floor-timbers; and the keelson, floor-timbers, and keel were bolted together. The floor-timbers were straight except at the ends, where they began to compass, that is, to turn upwards. The futtocks were next attached to the floor-timbers; these were the curved or compassing timbers that formed the curved sides of the ship. The timbers were placed very close together, and were doubled amidships and near the masts where a great strain was expected. Clamps were heavy planks running horizontally on the inside of the timbers to support the ends of the deck-beams. Partners were strong pieces of timber bolted across the deck-beams to support the masts, the heels of which were to be stepped on top of the keelson. The frame was further held together with a multitude of standing, lodging, and hanging knees, all made of oak. The ship-wright always searched for crooks of timber, which he cut up most carefully to avoid waste. The elaborate construction of the bow and stern was designed to resist the straining of the rudder and the anchor-cable as well as the battering of the seas.

While under construction the hull was shored up and a staging was built round it on which the ship-wrights could work. The planking was fastened to the timbers by wooden pegs or tree-nails made of heart of oak and driven in with a wad of oakum to stop any leaks. Reckoning the outside planking, the timbers, and the inside planking or ceiling, the sides might be almost 2 ft thick. The outside planking was carefully caulked with oakum between the seams. This heavy construction left unventilated spaces between the timbers, and as ships were built in the open so that rain-water lodged in the hull, conditions were favourable for wood-rot. Fortunately, most ships had much reserve strength in their massive build. It is difficult to realize the amount of wood, mostly oak, that went to build a big ship. A large warship required some 2000 oak-trees, each of them needing a century to reach maturity; wood which had matured more quickly was unsuitable for ship-building because it split too easily. These trees could not have been grown on less than 50 acres of woodland, which would be left stripped.

The weight of timber used accounts for the difficulties always facing the builder in launching a new ship. If the tide was not high enough to float the heavy hull out of the dock it was very difficult to shift it with wedges, screws, and winches. For this reason, though it remained usual to build large ships in docks, all other sizes were constructed above the water-level on hard ground. When the hull was ready a cradle was built round it; launching-ways were laid towards the water; the cradle was supported on the greased ways; the keel-blocks were removed; and the ship was ready to be launched down the greased ways at high water.

The new ship would be taken alongside a sheer hulk to have her masts stepped, after which she would be rigged. The buoyant wooden hull would have to be ballasted before it could be safely sailed.

Tonnage. The tonnage of a ship was an arbitrary figure meant to indicate the carrying-capacity of a ship engaged in the Bordeaux wine trade. The unit was a tun of wine in two butts of 252 gallons, estimated in 1626 to occupy 60 cu ft, allowing for the waste space due to the shape of the casks. In 1626 a ship 63 ft long and of 26 ft beam was calculated to measure 207 tons by the 'old' measurement, which gave her average cargo-capacity or net tonnage, and 276 tons by the 'new' measurement calculated to discover her dead-weight cargo-capacity or gross tonnage. The calculation of tonnage led to the invention of different rules and formulae worked out empirically, for the science of the time was unequal to extracting the exact measurement, which has become possible only in modern times.

VI. DECORATION

The decoration of ships is not functional and may therefore seem to be of little importance, yet it meant a great deal to both the ship-wright and the seaman, perhaps in different degrees. It also had a national significance. Proud ships suggested a disdain of enemies very encouraging to morale. The most costly decorations were to be found upon vessels owned by the king or the state. The fighting-galley of the Mediterranean often sported a profusion of fine works of art in the form of large gilded figures entwined around the stern and quarters. Throughout the sixteenth century the ships in northern waters were principally decked out with paint-work and very little carving: perhaps a series of blind archways or panels along the side and at a height above the water-line to continue under the gunwale at the waist, painted in bright colours. This frieze was sometimes of a geometrical pattern, and often was a design of entwined straps picked out in paint. The figureheads were generally small heraldic beasts crouching at the end of a galleon's beak-head. An example is Drake's *Golden Hind*, renamed after the crest of Sir Christopher Hatton, which one imagines must have adorned this famous ship as a figurehead. A coat-of-arms might be painted on the upper part of the flat stern. On occasion all ships flew many pennants, streamers, and banners.

In the seventeenth century ostentatious display took control. It would seem that the ship-wright wished to embellish his work with heavy gilded ornament for which the sailor had little use. We find naval officers complaining that a heavy figurehead and even heavier quarter-galleries made ships labour at sea. The excellent pictures of the *Royal Prince* of 1610 (plate 22) and the *Sovereign of the Seas* of 1637 (plate 23) show how Charles I surpassed his father in expense; Charles II, although always short of money, was even more extravagant. The ships of all the other European countries reveal the same disregard of nautical convenience. The men-of-war show us elaborate figureheads, such as men on horseback trampling their enemies, women and cherubs being drawn in chariots by eagles, and many other full-length figures disporting themselves both fore and aft, with carved wreaths round the circular upper-deck gun-ports, elaborate belfries like sumptuous summer-houses or well-heads at the break of the forecastle, and with the bulkheads at the break of the poop, quarter-deck, and forecastle richly adorned (figures 299, 304). Merchant-ships were plainer but gallant enough. These ships look beautiful to modern eyes, but the carving must have got in the way at sea and served no functional purpose. Charming features were the hancing-pieces, little figures such as crouching hounds or sleeping babies, which fitted into the step where the rail abruptly altered height at the break in a deck. The originals of this fine carving have all disappeared long ago, but much remains in well executed miniature on contemporary models; the best examples are English. At the end of the seventeenth century the exuberance of ship-decoration was fairly generally curtailed in all European countries, as much because of change of taste as from any real dislike of the great additional expense which all these countries had willingly borne for the last century at least. Nevertheless, the ship-wright continued to place as much carving on a hull as he dared, and the sailor to complain of useless weight on bows and stern of his ship, which should be kept light and seaworthy.

VII. DEVELOPMENT OF THE SHIP, 1700–50

Considering the many signs of an increasing interest in the theory and practice of shipbuilding which showed themselves in the seventeenth century, it is somewhat surprising to note how slowly the ship developed during the next. The reason is probably that the wooden sailing-ship had been so far developed empirically by seamen and ship-wrights—naturally conservative when faced by the changeless conditions of the sea—that by 1700 it had nearly attained the peak of perfection then possible. For example, a large ship of some 2000 tons had practically reached the maximum size possible for purely wooden construction. It is noticeable that, when new methods of construction and propulsion took the western world by storm in the nineteenth century, the sailing-ship was for long able to hold her own, even against what proved to be overbearing odds, with minimum changes in her style.

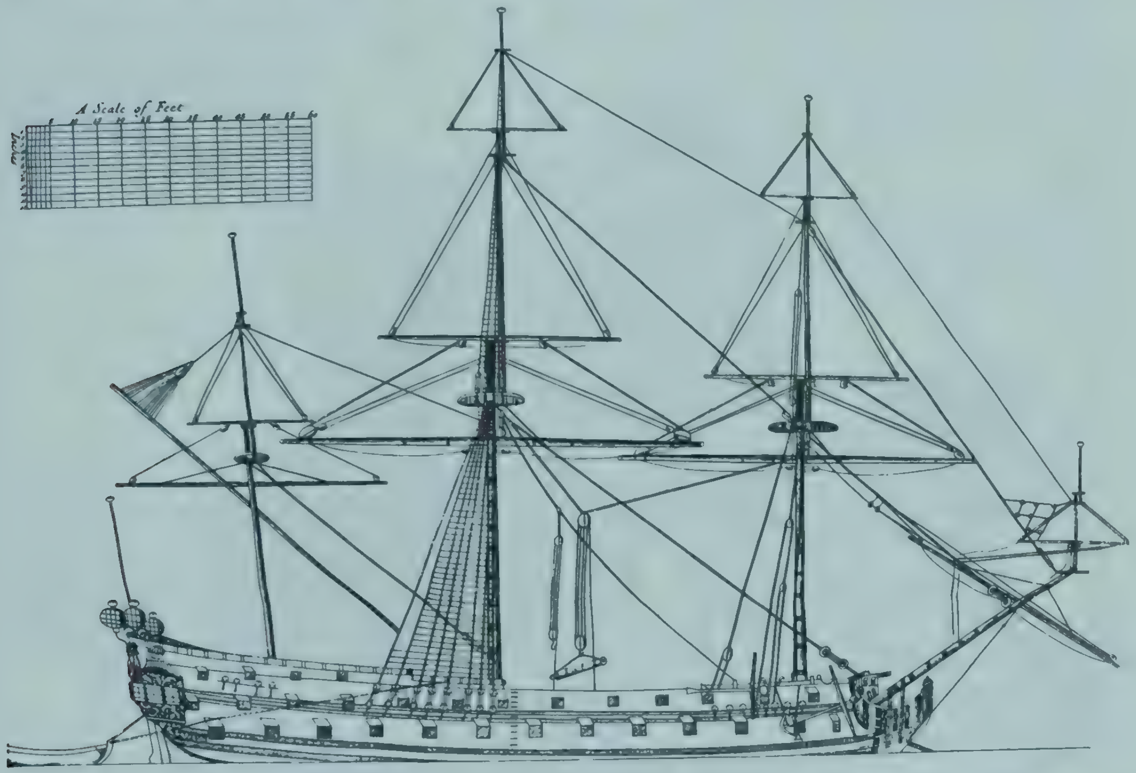

FIGURE 306—*Rigging plan showing masts and spars, with standing and running rigging, from Sutherland's work on shipbuilding of 1711 which names each item.*

Merchant-ships remained on the whole smaller than warships, a great many being still of about 200 tons to 400 or 500 tons. The finest merchant-ships were those employed by the English East India Company, of some 600 or 700 tons. Popular ships for long voyages were galley frigates, small ships built for speed which could be rowed in calms. They were not so heavily armed because it was hoped that pirates and other enemies would be evaded by superior speed. The ships of the various European countries had become more and more alike in general appearance, because national differences were being obliterated by the cosmopolitan sailorman.

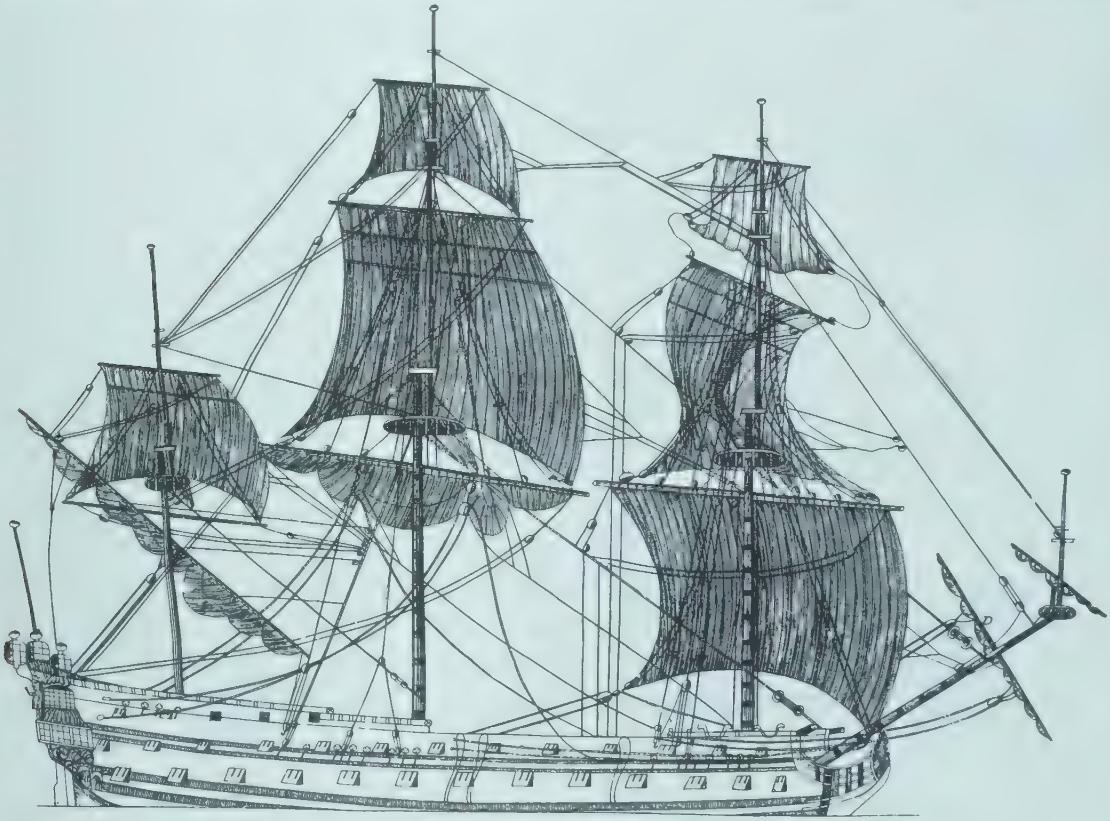

FIGURE 307—*Plan of sails and running rigging from the same work (1711). The two diagrams show fully and clearly the rigging of an English ship (to which that of Dutch and French ships was very similar) in 1700, before the spritsail topmast had been replaced by the flying jib-boom.*

A few characteristic changes in ship's rig became noticeable at the beginning of the new century (figures 306–9). Square mizzen topsails and topgallant sails were often set. There were now commonly two or three rows of reef-points in the fore and main topsails, and one or two rows in the mizzen topsail and fore and main courses. The heads of the topsails had become squarer, that is, broader, and the sails were deeper in comparison with the courses. The use of fore-and-aft staysails between the masts has been mentioned (p 486); now the spritsail topmast began to be abolished in favour of the jib-boom, sticking out from the bowsprit end to boom out the tack of the new flying jib. In England the jib was adopted in the Royal Navy in 1702 and the spritsail topmast officially abolished from the rig of big ships in 1715. The awkward interim period is difficult to understand, especially as pictures and models show both the topmast stepped and the jib-boom in place, a seemingly impossible combination. The spritsail topmast, though derided by seamen today, held its own and can be seen in contemporary pictures—generally of Dutch whaling ships—until well into the century, but probably not after 1750. The steering-wheel was introduced about 1705, according to the evidence of English models in the National Maritime Museum at Greenwich. The cumbersome whip-staff, already described, was

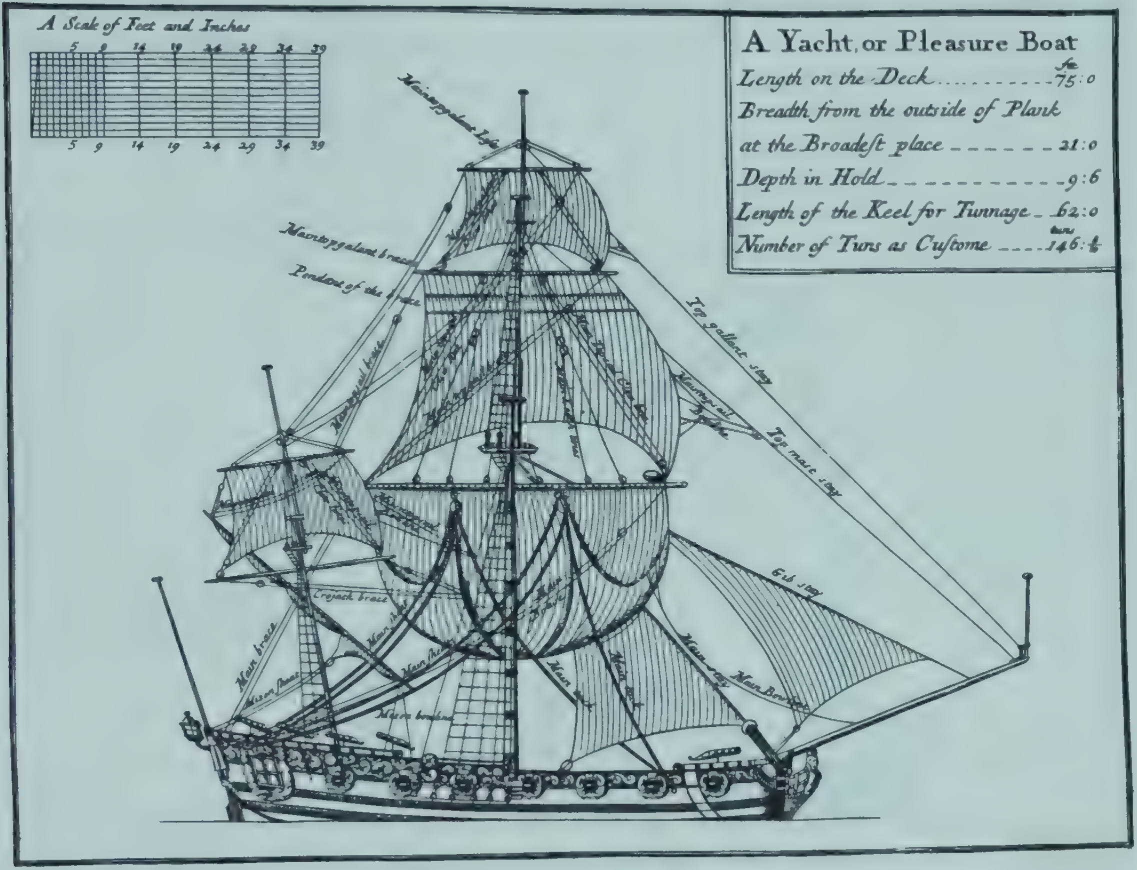
A Scale of Feet and Inches
5 9 14 19 24 29 34 39
A Yacht, or Pleasure Boat
Length on the Deck 75:0
Breadth from the outside of Plank
at the Broadest place ------ 21:0
Depth in Hold ----------- 9:6
Length of the Keel for Tunnage – 62:0
Number of Tuns as Custome ---- 146:4
Maintopgalant Lifts
Maintopgalant brace
Pendant of the brace
Maintopsail brace
Top gallant stay
Maintopsail Bowline
Top mast stay
Gib stay
Crojack brace
Main brace
Mizon sheet
Main sheet
Mizon bowline
Main tack
Main stay
Main Bowline

FIGURE 308—*Yachts were vessels of state used to convey kings and their representatives. They were introduced into England from Holland at the restoration of Charles II (1660). His royal yachts were manned by the Navy. By 1700 large yachts were ketch-rigged, that is, like a ship without a foremast. 1717.*

effective only in fine weather, for a sudden heavy sea could wrest it from the hands of the helmsman. After 1705, in bad weather the tiller was controlled by tackles led to the drum of a winch which was turned by the steering-wheel on the quarter-deck.

The fashion in decoration also changed at the turn of the century and a figure of a lion, crowned or uncrowned, became very popular. The name of Dutch ships was indicated by a coat-of-arms or device carved on the upper part of the flat stern. This was called the tafferel or taffrail, meaning a picture. The stern and quarters of ships were decorated with lighter, simpler carvings, which became even more delicate as the century progressed. Heavy gilt carvings were abandoned except by the royal yachts (figure 308) and important men-of-war. The broadside under the rail was decorated with a painted frieze, interrupted by the upper-deck gun-ports.

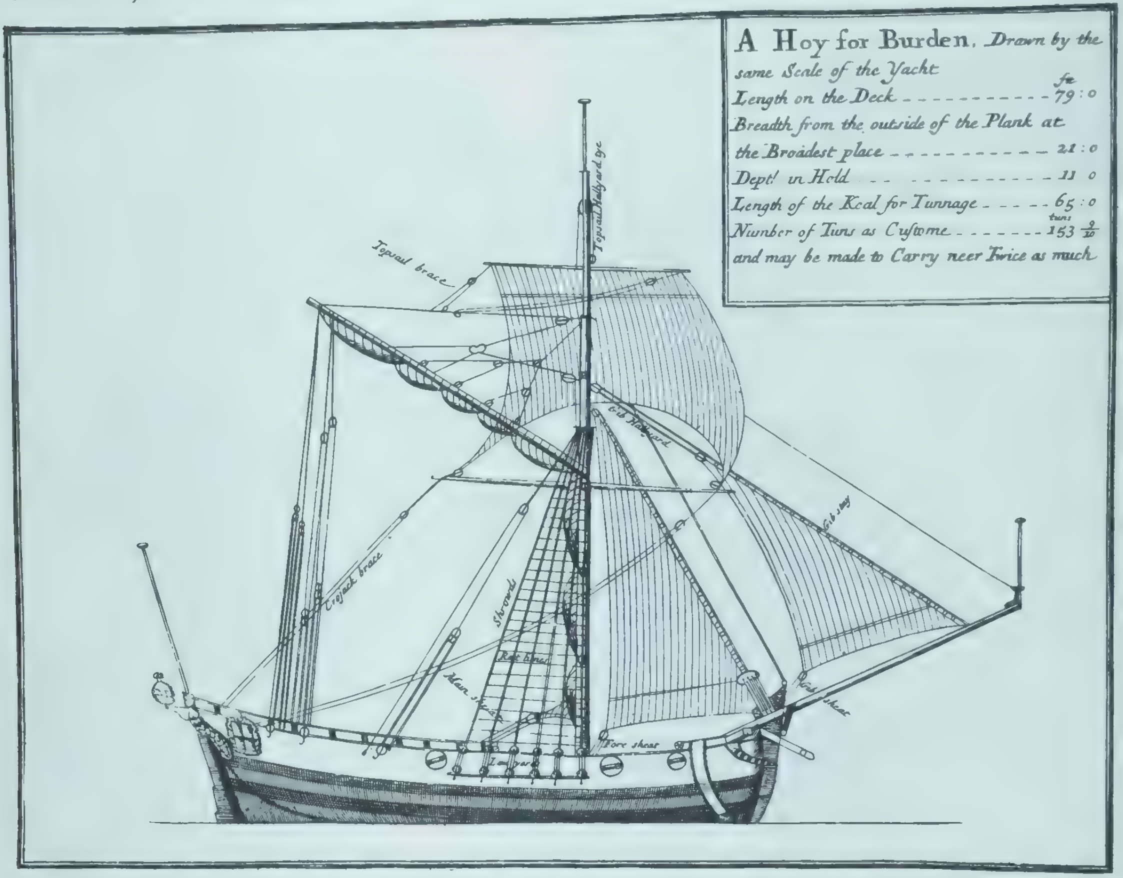
A Hoy for Burden. Drawn by the
same Scale of the Yacht
fe
Length on the Deck - - - - - - - - - - - - 79 : 0
Breadth from the outside of the Plank at
the Broadest place - - - - - - - - - - - - 21 : 0
Dept! in Hold - - - - - - - - - - - - 11 0
Length of the Keal for Tunnage - - - - - 65 : 0
tuns
Number of Tuns as Custome - - - - - - - 153 9/10
and may be made to Carry neer Twice as much
Topsail brace
Topsail Halyard tye
Crojack brace
Shrouds
Rat lines
Main sheat
Lanyards
Fore sheat
Gib Halyard
Gib stay
Gib sheat

FIGURE 309—*During the seventeenth century some coasting-trade was carried on in hoys, beamy fore-and-aft-rigged vessels, with square-sails for running before the wind. 1717.*

Merchant-ships still sailed fully armed against pirates and other enemies. Of smaller vessels working on the coasting-trade, the hoys were fore-and-aft rigged (figure 309), and the herring-busses were square-rigged on three masts. Many two-masted brigantines and snows sailed from Baltic and Spanish ports. The snow[1] was the larger type, and was in fact almost a three-master, for a rudimentary third mast, the trysail-mast, was stepped just abaft the mainmast and from it was set the fore-and-aft mizzen-sail of the full-rigged ship.

When we consider the fine voyages of discovery and scientific investigation carried out by Dampier and Halley, or of privateering by Woodes Rogers, we can understand something of the capabilities of the little ships of the period when they were well handled. Big ships also progressed. In 1744 the *Victory*, of 100 guns, was wrecked on the Casquets—a three-decker at sea in November. This loss was attributed by many to folly and lamented accordingly, yet in 1759 Admiral Lord Hawke won the battle of Quiberon Bay, fought in another November gale, with his flag flying in the *Royal George*, a three-decker like the *Victory*. Well handled, well found ships were now invincible, except on a lee shore, where sailing-ships are always vulnerable. Presumably the experienced seaman would shun lee shores, but this precaution was not always possible. It is worth remembering that the sailing-ship, however well designed and constructed, was at sea always dependent on the seaman and the pilot. Without the power of the steam-engine, a sailing-ship was inevitably endangered under certain conditions. The master, caught out on a lee shore, was only reckoned at fault if his ship had driven ashore with an anchor and cable unused.

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[1] Dutch *snaauw*.

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19

CARTOGRAPHY, SURVEY, AND NAVIGATION TO 1400

CHARLES SINGER (I–VI), DEREK J. PRICE (VII), AND E. G. R. TAYLOR (VIII–XI)

I. NUMERICAL NOTATION

IN antiquity all activity in building, engineering, surveying, and many other techniques encountered an obstacle of a kind quite unfamiliar to us. This was the clumsy numerical notation to which the ordinary rules of arithmetic could not be directly applied. Astronomers, it is true, could employ the sexagesimal system which had been in constant use from early Babylonian times (vol I, ch 31). This gave ease of operation without the necessity of expressing any single number greater than 60. In ordinary life, the application of simple arithmetic, especially multiplication and division, was a laborious operation for which the help of the abacus or some other sort of counting-device had to be invoked. Not every intelligent man, even in the educated class, could carry it out; but such simple calculation is of special importance in connexion with surveying and map-making.

The earliest and simplest reckoning-apparatus was a board sprinkled with sand divided into columns by the finger, counters being used in calculation. Cicero, referring to this operation, speaks of an expert calculator as 'clever at handling the sand'. The counters, which could be shifted from column to column, had graven on them figures of the fingers and hand in various positions accepted as representing different numerical digits. These symbols remained in general use till late medieval times, and are still employed as Roman, as opposed to 'Arabic', numerals.

The true abacus began as a board with a series of grooves in which pebbles or *calculi* could be moved up and down: hence our word calculate. The form of the Greek abacus is obscure, but the more developed Roman type is well known and is still in general use in the east. It had an upper row of short and a lower of long rods (vol II, figure 694). Each short rod had a single perforated bead running on it, and each long one had four such beads. The first rod on the right was marked for units, the next on its left for tens, and so on to a million.

Our own decimal system of 'Arabic' numerals, giving each numeral a value according to its position and using a sign for zero, is of Indian origin although the ultimate source of its component inventions is a matter of some dispute. It reached Europe through Islamic channels during the revival of astronomy in the Middle Ages (p 521), but was not generally adopted, except for astronomical purposes, before the sixteenth century. The Greeks, whose numerical use of letters of the alphabet was almost as clumsy as the Roman system, often employed geometrical methods where we employ algebra, but their mathematical developments made little impression on the Romans. How slight was the mathematical knowledge, even of scientific authors, among the Latins may be gathered from the *Geometrica* and *Arithmetica* ascribed to Boëthius (480–524), 'the last of the ancients'. These elementary works represent the immediate mathematical legacy of classical antiquity to the earlier Middle Ages. Even when Rome had world dominion, Cicero bemoaned that 'the Greek mathematicians lead the field in pure geometry, while we limit ourselves to the practice of reckoning and measuring'.

II. TYPES OF MAP

Early maps are broadly divisible into four classes or grades. First there are rough outline pictures of a limited terrain with which the observers were familiar. Children and savages make sketches of this kind. If based on some kind of measurement they may reasonably be called maps. More exact surveys on these lines were constantly made in the ancient empires. Good specimens have survived from Egypt and Mesopotamia (vol I, figures 364, 367, 385). The Greeks regarded the Egyptians as the originators of geometry, or Earth-measuring, which was made necessary by the periodic obliteration of landmarks by Nile floods. Such surveys, of varying accuracy, were also made by the Greeks and Romans for the purposes of town-planning and for the legal establishment of ownership of property, but none seems to have been preserved.

Secondly, there are plans of part of the Earth's surface made on estimates of distances and directions reported by travellers—usually on the basis of time consumed in travelling—and collected by the map-maker. Maps of this kind were necessary to many major officials, especially in the centuries when the Roman Empire was at its greatest. They might be made either with or without a system of projection. True maps of neither type are known from classical antiquity, but we have something which is even more informative. About the middle of the second century Ptolemy (Claudius Ptolemaeus) of Alexandria, who well understood the principles of projection, wrote a 'Geography' possibly provided with maps. This book has come down to us, with the relevant measurements, so that though the original maps are lost they can be reconstructed. Ptolemy's work is considered below (p 508).

Thirdly, we may for the present purpose consider as maps plotted itineraries that act as guides to travellers by recording places and distances graphically but not directionally. We have surviving traces of these, as, for example, in the Peutinger table, to which we shall refer (p 515; figure 320).

Fourthly, and yet more marginal to technology, though sometimes described as 'maps', are attempts to represent the whole Earth, or even the universe. The place of these is in histories of science, of philosophy, or of religion.

III. THE CARTOGRAPHER'S TASK

For measurements on a larger or geographical scale the ancients were much less well equipped than for surveying in the proper sense. The ancient geographer, or rather his informant, could determine latitude by elementary astronomical observations either of the meridian transit of a star by night, or of the Sun's noon height at the equinox by day (ch 22). A very much more difficult problem was the determination of longitude. For this it is necessary to compare the local times of an astronomical event, such as an eclipse, either by having observers in two widely separated places or, by using standard tables, to compare the computed time at the place where the ephemerides were drawn up with the observed time in the place in question. The ancients, having no independent accurate timekeeper, never conceived of the measurement of longitude by using a portable chronometer; this was left for Gemma Frisius (1508–55) to suggest and to John Harrison (1693–1776) to achieve. The astronomical measurement of latitude was therefore reasonably accurate and satisfactory, but the complementary determination of longitude was much more arduous and inherently much more inaccurate (see table, p 583).

Thus for all longer journeys, whether by sea or land, the ancients depended almost entirely on some form of dead-reckoning, a method which is inherently unreliable. This is among the several reasons for the distortion of ancient maps. The principle of triangulation, however, had long been familiar. Trigonometry had been formally inaugurated by Aristarchus of Samos (third century B.C.), but could not be applied for sufficiently great distances. Despite such discouraging obstacles, the general problem of the form of the countries of the Empire urgently demanded some sort of solution. The determination of the frontiers of provinces, the demands of trade, the distribution of the fleet, all made the need of a general map of the Empire evident. None of the Roman maps, however, has survived, though we learn of them from Cicero (106–43 B.C.), Vitruvius (fl A.D. 1), Seneca (d A.D. 65), Pliny (d A.D. 79), Suetonius (*c* A.D. 121?), and others. Earlier still, Varro (116–27 B.C.) indicates the ancient religious associations of such documents, for he relates that a map of Italy, engraved on marble, had a place in the temple of Tellus at Rome.

Julius Caesar (100–44 B.C.) planned a complete survey of the Empire. Like his calendarial reform, it was perhaps suggested by ideas emanating from Alexandria. In the event, the execution of the scheme fell to Augustus. The survey was finally superintended by Augustus's son-in-law Marcus Vipsanius Agrippa (63–12 B.C.) and was completed in 20 B.C. after nearly thirty years' work. Agrippa wrote a commentary based on this map. It was fairly accurate for the provinces of Italy, Greece, and Egypt, but other countries were only very roughly surveyed. The survey was possible because the Empire was furnished with roads marked out with milestones (vol II, figure 463) and patrolled constantly by a regular service of skilled *agrimensores* or land-measurers. Their work, incorporated in the reports of provincial governors, became available at headquarters. From this mass of material a huge map was prepared, which was exhibited in Rome in a building erected for the purpose. It was perhaps the basis of later strategical surveys, a surviving copy of one of which is known as the Peutinger table (figure 320).

Some idea of the manner in which the main routes of the Empire were surveyed may be gained from certain monuments, notably the inscribed marble pillar of Autun (*Augustodunum*). This gives—or gave, for most of it is now lost—the distances of places on the road from Autun to Rome, such as *Autissiodorum* (Auxerre), *Bononia* (Bologna), and *Mutina* (Modena). Somewhat similar inscriptions have been found in Belgium, Spain, Britain, and elsewhere. Of special interest to English readers is a bronze bowl from Rudge Coppice (near Marlborough) in Wiltshire, around the edge of which are written, in second-century script, the names of a number of sites on Hadrian's wall.

IV. ESTIMATE OF THE SIZE OF THE EARTH

An essential to map-making on the geographical scale is some conception of the form of the Earth. Pythagoras (fl *c* 531 B.C.) held that it was a sphere, and this doctrine was firmly established by the teaching of Plato (*c* 429–347 B.C.), Eudoxus (*c* 370 B.C.), and Aristotle (384–322 B.C.). The spherical form of the Earth was commonly accepted by the educated public from then onward—even, in spite of statements to the contrary, through the Middle Ages (p 518).

This idea once grasped, any major part of the Earth's surface could be represented only by the acceptance of some geometrical operation of projection, as is now familiar through the use of lines of latitude and longitude. It happened that the fourth century B.C. was not only a period of great mathematical advance by the Greeks but a period of rapid expansion of their knowledge of the Earth's surface and of its inhabitants through the activities of merchants, explorers, and military ventures. This widening horizon was especially due to the conquests of Alexander and the journeys and writings of his generals, admirals, and other officers. Good use of this new information was made by Dicaearchus (fl *c* 300 B.C.), a pupil of Aristotle. He sought to make a map of the known world as related to a parallel of latitude through Gibraltar and Rhodes, extending eastwards through the Caspian Gates—not far from Teheran in Persia—and along the base of the Hindu-Kush (figure 311). This line is, on the whole, notably correct.

Eratosthenes (*c* 275–*c* 194 B.C.), librarian of Alexandria, is, however, the real father of projective mapping, basing it on his own brilliant feat of measuring the globe (figure 310). Eratosthenes sought to make geography a science. He adopted the parallel of Dicaearchus but also drew a second, though less accurate, parallel from Ethiopia to south India. In doing this he regarded their latitudes as similar because of the supposed similarity of their climates, plants, animals, and peoples. Between these two parallels he fitted the reported Indian distances, thus twisting the Indian peninsula to point south-east. The over-estimated Indus was supposed to follow a southerly direction, with its mouths pulled far south of the tropic, together with the coast of the fish-eaters (Ichthyophagi) of Baluchistan, and most of the Persian Gulf. Thus the mapping worked along from India, resulting in many errors that were transmitted farther west.

Eratosthenes made his famous measurement of the Earth on the assumption that it was a perfect globe (figure 310). He presumably started with three propositions:

(*a*) That at Syene on the Nile (the modern Aswan) at noon on midsummer day an upright rod casts no shadow, being on the tropic.

(*b*) That Syene is 5000 stades from Alexandria.

(*c*) That Syene is directly south of Alexandria.

Now it is clear that, if we consider the Earth as a sphere, then the ratio

$$\frac{\text{angle at centre subtended by 5000 stades}}{\text{four right-angles}} = \frac{\text{5000 stades}}{\text{circumference}}.$$

The problem is, therefore, to determine the angle at the centre subtended by 5000 stades. But if on midsummer day the shadow cast by an upright rod at

Alexandria is measured, then we shall be able to estimate the angle that the Sun's ray makes with the rod. Since, however, the Sun is so vastly distant from the Earth, the Sun's ray at Alexandria is in effect parallel to the Sun's ray at Syene. Therefore the angle that the Sun's ray makes with the rod is equal to the angle subtended by 5000 stades at the Earth's centre. There is thus but one unknown—the Earth's circumference—in our equation. The circumference of the Earth so obtained is a very fair estimate. The angle to be measured was found to be 1/50 of four right-angles. Since the distance between Alexandria and Syene was 5000 stades, the circumference of the Earth was 50 × 5000 = 250 000 stades. Eratosthenes was aware of various chances of error, and in fact Aswan is not on the tropic but 37 miles north of it, and not on the same longitude as Alexandria but three degrees east of it. Bringing his figure up to 252 000 stades, he reckoned 700 stades to a degree.

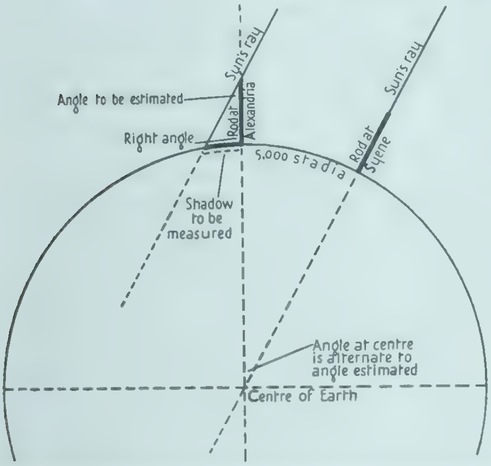

FIGURE 310—*Eratosthenes' method of measuring the length of a degree of the meridian, from which the circumference of the earth was calculated.*

Unfortunately, it is not certain what the stade meant exactly to him or to other geographers. It was 600 'feet', but there were variants according to the foot-standard used, while long distances were not actually measured but interpreted into stades from the time taken to cover them. Writers of Imperial Rome counted at the rate of $8\frac{1}{3}$, or roughly 8, stades to their mile. Assuming that Eratosthenes was reckoning in terms of these ordinary stades his grand total is some 12–14 per cent in excess. At ten stades to the mile it is nearly correct.

On the globe thus measured Eratosthenes proceeded to fit the known world by calculating its north–south breadth and east–west length along two great lines intersecting at Rhodes (figure 311). The breadth extended from the Somali coast—for the torrid zone was known to be habitable so far south—to Thule near the Arctic circle. The length along the great parallel worked out at 70 800 stades from Cape St Vincent to the mouth of the Ganges, or, with allowances for the projection of India and possible islands, at 78 000. This is only about two-fifths of the way round the globe on that parallel. What of the remaining three-fifths? Sailing west from Spain, would there be open sea to India or some 'outer dwellers' on the way?

The work of Eratosthenes was reviewed by the great astronomer Hipparchus, who made observations from 161 to 126 B.C. He attacked the procedure in detail, and stressed the need of a better groundwork of observations. He could add some latitudes from the work of explorers, but the weak point of ancient geography was always lack of longitude determinations (p 503).

Any interest the Romans might have had in science would have found plenty of scope in geography. The Empire, as established by Augustus in 27 B.C., enjoyed two centuries of almost unbroken peace. Civilization spread, travel was safe, and there was much mingling of races. Writers of the time, impressed by the size of the Empire, often spoke as if there were nothing but a barbarian fringe beyond. Though the Romans did little exploration for its own sake, some of their traders went beyond the legions, while others sailed to India; even of China a little was heard by land and sea. There are several works of Imperial times that add to our knowledge of geography, but very few did anything to advance the technique of map-making.

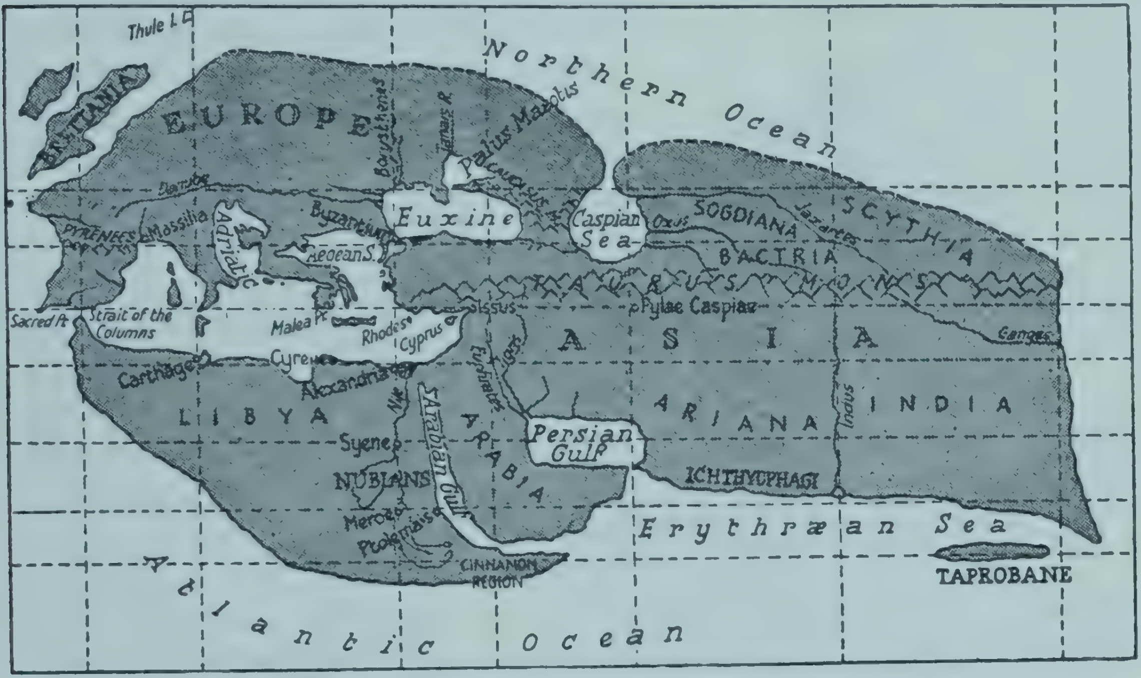

FIGURE 311—*The world, reconstructed according to Eratosthenes' ideas.*

V. THE PTOLEMAIC MAPS

Important for map-making, however, was Marinus of Tyre (*c* A.D. 120). His 'Correction of the Map' used the latest reports to extend the map far to the east and south. His results were sometimes extravagant because he did not allow for the exaggerations, halts, and divergences of travellers. He had a very simple sort of projection, with parallel meridians drawn at right-angles through degree-points spaced in due proportion along one important parallel—that through the island of Rhodes. His successor Ptolemy, who alone records the work of Marinus, permits this method, but does so only for maps of provinces, because within such small areas the distortion is not considerable.

Ptolemy (fl A.D. 121–51), one of the greatest figures of ancient science, made an elaborate effort to map the known world. His maps are lost (p 510) but he provided ample material for remaking them. They can be reconstructed from his figures of latitudes and longitudes, and are surprisingly detailed and reasonably well shaped (figure 312). Even for the map of Ireland, never reached by the Roman legions, he has many names.

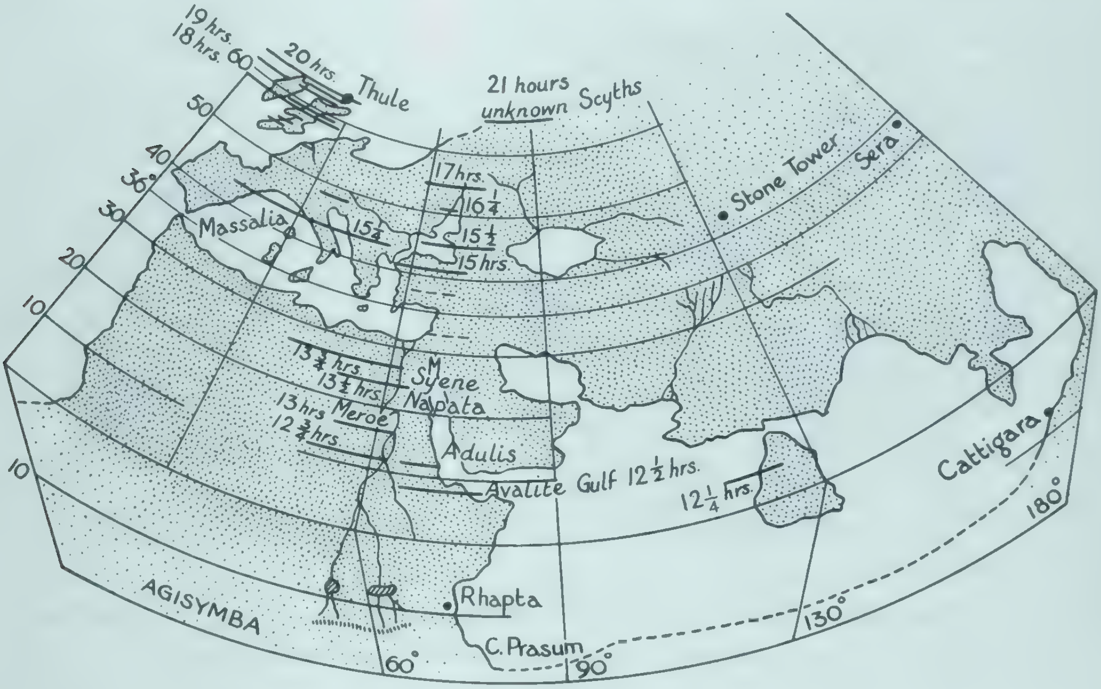

FIGURE 312—*The world according to Ptolemy, using his first projection.*

Ptolemy was interested in mapping but not in geographical description. In his 'System of Astronomy'—the *Almagest* of the Arabs and of the later Middle Ages—he explained how to put the known Earth on the globe, half-way round in the north temperate zone and extending southward into the torrid zone. He also tells how 'climates' are determined by their longest day and by the length of shadows at the equinoxes, and defines an elaborate series of such climates by lines of latitude up to the Arctic circle (figure 330). In his 'Geography' he insists that mapping should be based on astronomically fixed points, though practically no longitudes were then so derived. The latter he obtained mostly by computation.

Ptolemy's 'Geography' is basically a list of 8000 places, to each of which is ascribed a longitude and a latitude, but the vast majority of these positions are merely reckoned from itineraries. His data provide material for drawing either a set of 26 land-groups, as he recommends, or another of 63 smaller regions, including, for example, 4 provinces in Gaul. Unhappily Marinus and Ptolemy adopted for the circumference of the globe the poor figure of 180 000 stades on the equator, making 500 to the equinoctial degree or 400 on the parallel of Rhodes.[1] This error only partly accounts for the fact that the Mediterranean is exaggerated as 62°, instead of about 45°, but the error yet further accumulates eastwards.

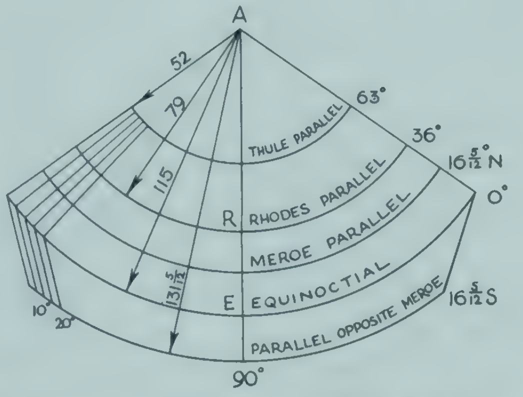

FIGURE 313—*Ptolemy's first method of projection. The scale unit is 1° of the great circle of the globe. The parallel of Rhodes is correctly divided at 5° intervals (each equal to 4 units) and meridians are drawn from* A *through these divisions.*

Ptolemy's task was simplified in that he had only to map the 'known habitable world' of his day, which after a critical examination of the data he considered to cover 180° in longitude, 80° in latitude. Hence he could use a modified simple conic projection, taking as his standard parallel that through Rhodes (36° N), a datum line long in use by his predecessors. It has the advantage that, as just mentioned, the spacing of the meridians along it was at the round figure of 400 stades to the degree. For the scientific map Ptolemy suggests two projections. In his construction for the first projection (figure 313) he drew a great circle of the globe (containing 360 units of one degree), the radius therefore being $57\frac{3}{11}$ units. Drawing a tangent cone at 36° he obtained a radius from its vertex of 79 units for the parallel of Rhodes. His northern limit was 63° N, the parallel assigned to Thule, his southern limit $16\frac{5}{12}$° S, a parallel he chose to correspond with that of Meroë at the same distance north of the equator. All the parallels were correctly spaced, and the standard parallel truly divided, the meridians being ruled from the vertex of the cone through these divisions. The second projection shows both the parallels and the meridians (except one) as curved. The same number of meridians is drawn as before, each parallel being correctly divided, that is, spread from four units apart on the parallel of Rhodes to $2\frac{1}{4}$ apart on that of Thule. The improvement is obvious, though there is increasing distortion with increasing distance from the central meridian (figures 314, 315).

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[1] See p 506. The accuracy of Ptolemy, as of Eratosthenes, is bound up with the problem of the length of the stade.

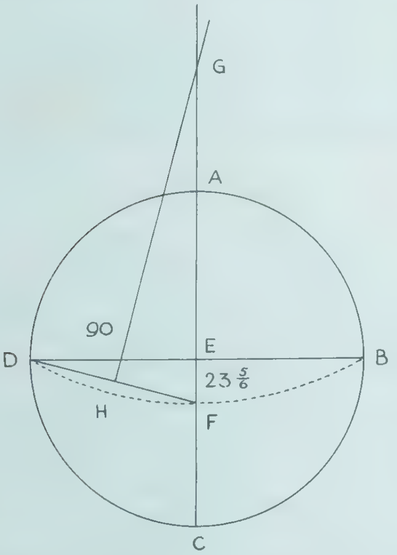

FIGURE 314—*Method of finding the centre for the arcs of the parallels in the second projection. The unit of measurement is 1° of the great circle, that is 500 stades. The radius of the circle* ABCD *is 90 units;* EF *is 23 5/6 units, so that* E *is on the northern Tropic (arc of Syene), and* F *on the equinoctial (equator).* HF ($= \frac{1}{2}$ DF) *is calculated as 46 11/20 units. With* HG *perpendicular to* DF, *the triangles* GHF *and* DEF *are similar, and* GF *can be calculated as 181 5/6 units. Then* G *is the required centre and the arc* DFB *represents the equator.*

For the history of geographical maps it is unnecessary to follow the decline of the technique in the Middle Ages. Ptolemy's methods of projection were forgotten, and geographical mapping in the scientific sense ceased in the west until the recovery late in the fourteenth century of Ptolemy's Greek text with a representation of his maps. Medieval shipping, however, demanded sailing-directions and these, from the late thirteenth century, were expressed in so-called *portolani* or 'portulan charts' which are considered below (p 526).

VI. SURVEY IN CLASSICAL TIMES

For constructing the buildings of remoter antiquity, for much ancient irrigation, and for many other public works, preliminary surveys were obviously needed. None has survived. Mention has been made of land-measurements by the Egyptians (vol I, p 540), and they had ways of determining the horizontal and the difference in height between two points. They are known to have used the plumb-level (vol I, figure 314), the set-square, and several other simple surveying-tools. There still exist an Egyptian sighting-instrument, the *merkhet* (vol I, figure 47), and the remains of a *groma* (figure 316). Such devices passed to the Greeks, Romans, and other peoples.

We cannot discuss all the surveys of classical antiquity, but two famous examples suffice to illustrate the advance in the possibilities of surveying introduced by early Greek science. An inscription records a process of tunnelling by the engineers of Hezekiah, twelfth king of Judah (*c* 715–*c* 687 B.C.). He built the conduit leading water from a spring at Gihon to the Pool of Siloam in Jerusalem *c* 700 B.C. Though the direct distance was only 366 yd, the engineers, to avoid certain obstacles, had to tunnel some 583 yd, with curves in three dimensions.

They had no effective means of mapping their track and were forced to sink shafts to find out where they were. In the end, the two headings nearly missed each other. The completion of the tunnel is commemorated in an early Hebrew inscription (vol I, figure 559).

Greater accuracy was shown in some Greek constructions of somewhat later date. Thus *c* 550 B.C. the engineers of a tunnel at Samos, of about 1200 yd, worked from both ends and met with an error of about 5½ yd (vol II, p 667 and figure 611). Such results could have been secured with the instruments enumerated above (p 510), together with some form of the water-level as described by Vitruvius, who admits that his own methods were of earlier Greek origin. It is probable that the Samos engineers worked on a simple system of triangulation.

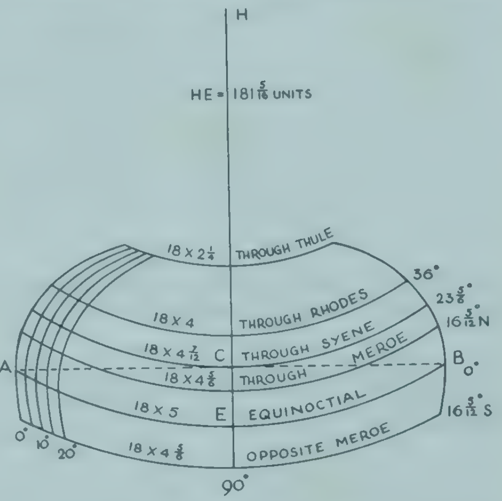

FIGURE 315—*Ptolemy's second method of projection. The projection is centred on the parallel through Syene (the Tropic), the equinoctial (or equatorial) semicircle passing through the points AEB where* AB = *180 units,* CE = *23 5/6 units. Parallels are correctly spaced on the central meridian* HE *and correctly divided at 5° intervals. The meridians are curves drawn through the dividing-points.*

Among the Romans the standard of surveying must have been high, as is indicated both by their building achievements and by Vitruvius (ch 10). They held that the art of mensuration was at least as old as Rome itself and that it was first practised by their priests for religious purposes. Familiarity with the processes spread in Imperial times, and a regular school of surveying was established at Rome. The chief instrument in general use was the *groma*, a slight development of the Egyptian instrument (figure 316). One of the lineals was used for sighting, the other to determine the direction in the field at right-angles thereto. Since both agriculture and town-planning were mainly on rectangular lines (ch 11), this instrument was of wide application. It was the custom to erect a *groma* in the centre of a military camp.

The Roman surveyor must have used also an instrument for measuring angles subtended at the eye by two distant points. Its original very simple form was doubtless that of two wooden rods jointed together at one end, each piece provided with a terminal peg or sight at the other. To secure accurate horizontality the surveyor had at his disposal a water-level or *chorobates*. This, as described by Vitruvius, was a straight plank about 20 ft long with supports at the ends,

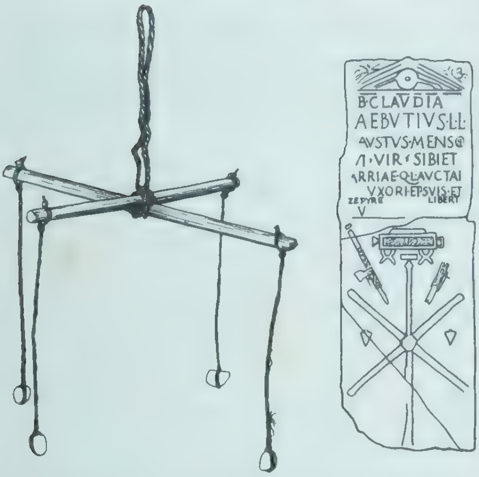

FIGURE 316—(Left) groma *from the Fayum;* (right) *tombstone of a Roman* mensor *found near Turin.*

steadied by cross-pieces. These cross-pieces were marked with lines perpendicular to the plank, which was adjusted till the lines corresponded to plumb-lines. Since wind might disturb the plummets, accuracy was ensured by a groove in the top of the plank, partly filled with water. The height of the water from the level of the plank could easily be measured at either end.

Apart from such instruments as compasses, set-squares, measuring-rods, and chains, these almost completed the ordinary equipment of the Roman surveyor. Some surveying-instruments of the time have been found at Pompeii (figure 317). Whatever the common practice, an exceptional standard of precision was attainable by the use of two instruments, a *dioptra* and another type of water-level described by Hero of Alexandria (fl *c* A.D. 62). These represent the highest development of surveying-apparatus known to have been reached in antiquity (figures 360, 361).

Vitruvius gives a method of estimating the distance from the observer of an inaccessible point on the same level as himself, such as on the opposite bank of a river. A straight line along the near bank is measured by rolling along it a hodometer or 'road-measurer', an instrument consisting of a wheel of measured circumference, the revolutions of which are automatically recorded. From each end of the straight line measured by the hodometer a sight is taken. The angles and the base being thus determined, a triangle, congruent to that formed by joining the point on the far bank to the extremities of the measured line, can be constructed on the near bank. The vertical height of this triangle can be measured, and a simple arithmetical calculation gives the distance of the point from the observer. A comparable device could be used for measuring inaccessible heights (figure 318). The work of Vitruvius was first printed in 1486 at Rome and early circulated in an Italian translation. From it Leonardo da Vinci (1452–1519) doubtless obtained hints that enabled him to design his hodometer (figure 319).

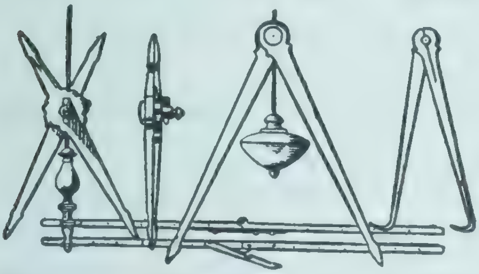

FIGURE 317—*Mathematical instruments found at Pompeii—compasses, calipers, rules, level, etc.*

VII. SURVEY IN THE MIDDLE AGES

During the Middle Ages surveyors continued to use only the most simple direct measurements, with line or rod or pacing for length, and with the *groma*, the plumb-line, and a primitive water-level for setting out right-angles and establishing verticals and horizontals. There are many medieval texts on surveying that describe indirect methods of measuring the height of a tower or an inaccessible wall by the theorem of similar triangles. The most simple of such devices is a staff of known height which the observer can use to 'cover' the tower when his eye is in a suitable position. Another simple device is to measure the length of the shadow of the tower at such a time that the Sun is at an altitude of 45°, so casting a shadow equal in length to the height of the tower. More complicated is the use of the shadow-square (p 528), either inscribed on the dorsum of an astrolabe (figure 329), or incorporated into a separate instrument such as a geometric quadrant or a geometric square. Using any of these, it is possible to sight the tower or wall directly, or sight the Sun in order to measure the ratio of shadow-length to object-length at the time of observation. All these indirect methods show considerable ingenuity, and there are many refinements by which the height of the observer's eye is taken into account, or a mirror is laid on the ground so that the viewpoint is accurately established.

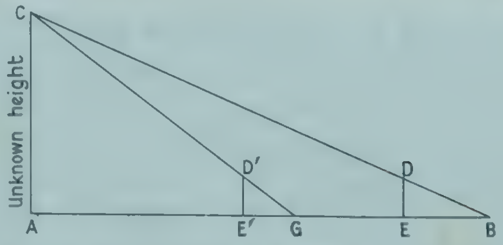

FIGURE 318—*Principle of measurement by similar triangles. If* AB, DE, *and* BE *are all known, then* $AC = \frac{AB.DE}{EB}$. *If the distance* AB *cannot be measured, the staff* DE *is advanced the measured distance* BG *and the observation repeated. Then* $AC = \frac{AG.D'E'}{E'G} = \frac{(AB-BG)D'E'}{E'G} = \frac{AB.DE}{EB}$. *Hence* AB *is determined and the first equation can be solved.*

Such indirect methods are usually described for measurements in the vertical plane, while similar applications to the horizontal plane are singularly rare. It might be suggested that such technical procedures were too familiar to demand description. A more likely explanation is that nearly all these texts were written by geometers anxious to impress powerful patrons with their skill. But in practice it is seldom necessary to make indirect measurements of heights of buildings. Moreover, such information would have been of little use to the gunner or architect devoid of mathematical skill.

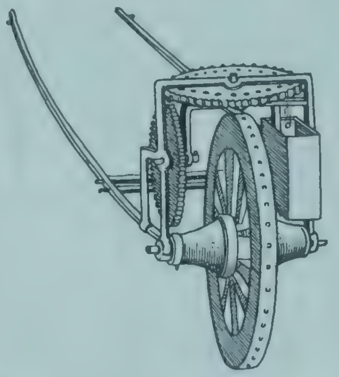

FIGURE 319—*Leonardo's hodometer, counting the revolutions of a wheel of known circumference. The recording by stones dropping into a box is taken from Vitruvius. Similar devices with clock-face recorders were much used in the eighteenth century.*

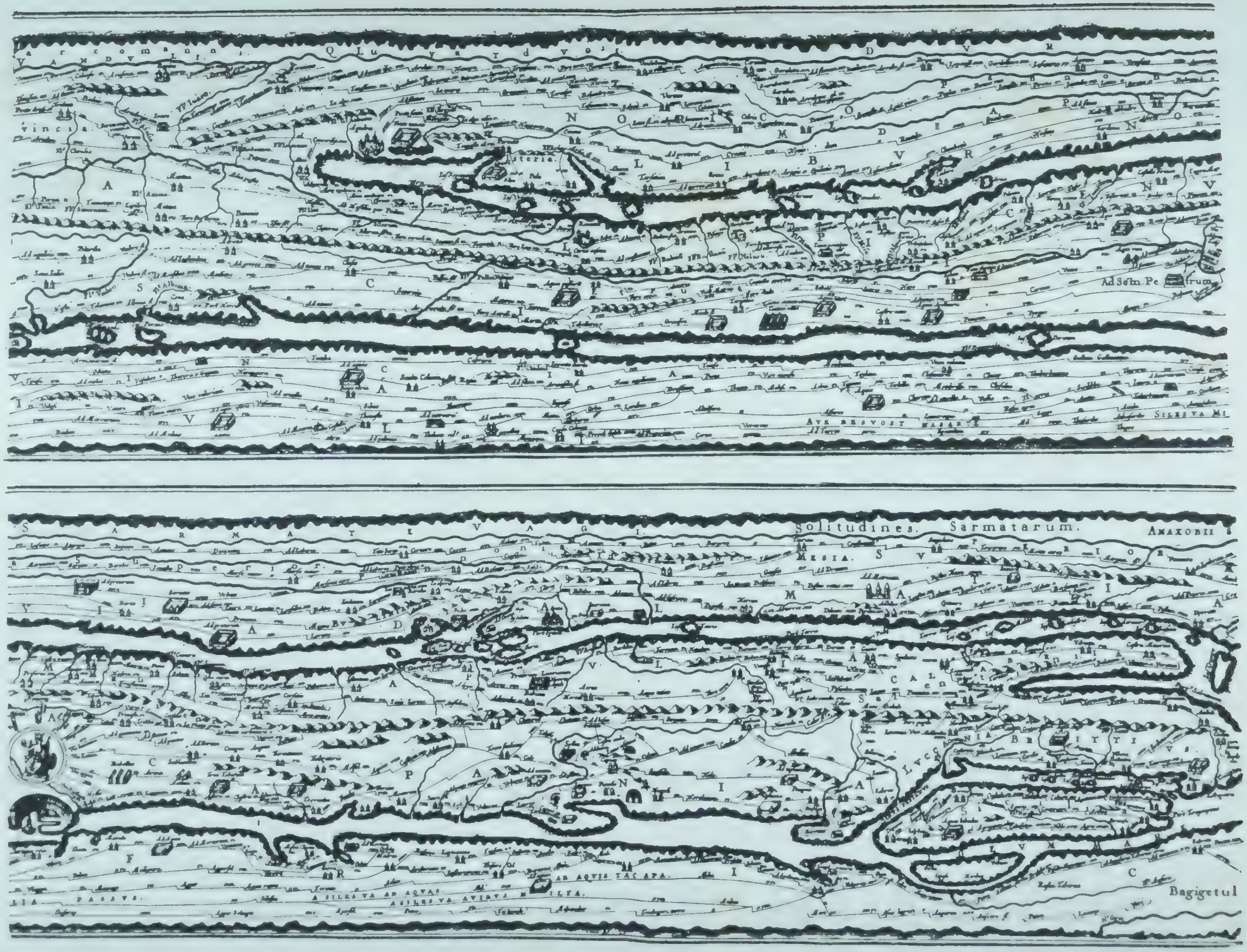

FIGURE 320—*A portion of the Peutinger table, showing Italy, the Dalmatian coast* (above), *and the N. African coast* (below). *The seas intervening are so schematized that they almost disappear.*

One way in which the accuracy of medieval surveying techniques can be assessed is the orientation of churches. Measurement of some 700 of them in Britain shows a standard deviation of the order of ±14° about a mean which is 10° N of E. This is a very crude result. It is probable, therefore, that the craftsmen orientated the buildings merely by noting roughly the direction of sunrise at whatever time of year operations began.

Maps prepared by medieval surveyors confirm that only the basic direct measurements of length and right-angles were used. These maps show certain points of similarity with an Egyptian map (vol I, figure 385) and also with the Peutinger table (figure 320). Medieval maps have usually a variable scale, interesting regions being magnified at the expense of the less important. On the whole, however, distances are recorded more accurately than angular bearings. Furthermore, obscurities are often introduced by the addition of views in elevation of buildings, mountains, and other objects of interest which are superimposed on the ground plan (figure 322). Another feature of medieval survey plans is that, although the map may be orientated with E at the top as with *mappae mundi* (p 519), S and W are at the top almost as frequently. In some cases, even, the cardinal points are at the corners of an oblong sheet.

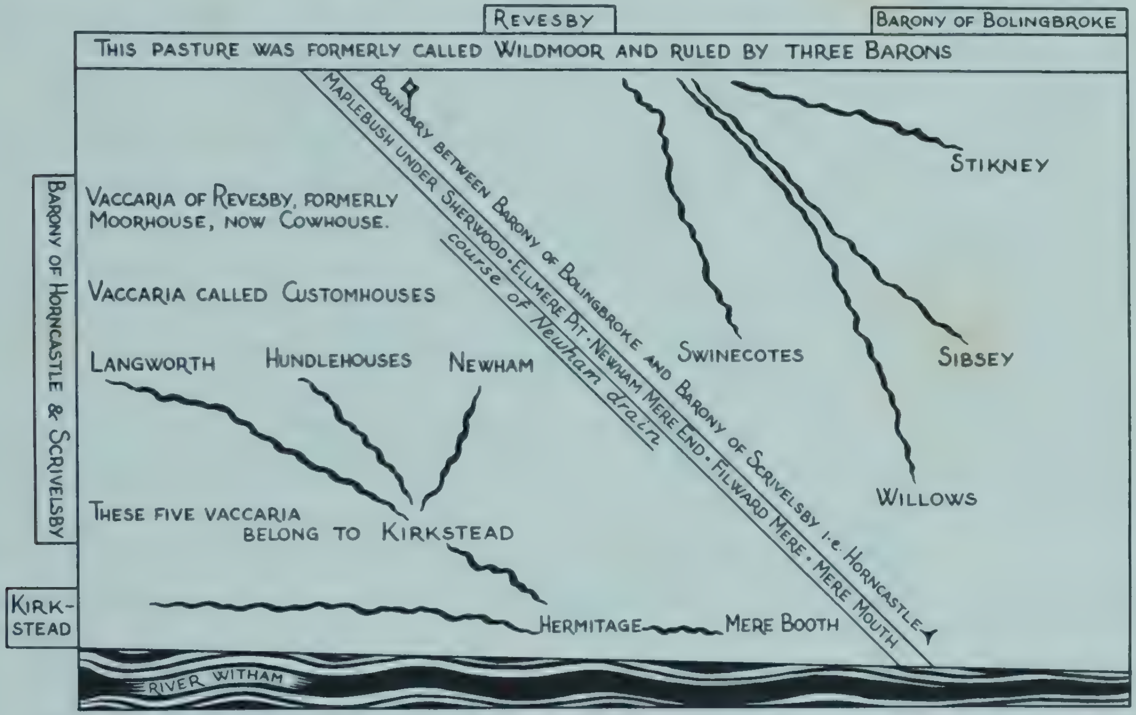
REVESBY
BARONY OF BOLINGBROKE
THIS PASTURE WAS FORMERLY CALLED WILDMOOR AND RULED BY THREE BARONS
BOUNDARY BETWEEN BARONY OF BOLINGBROKE AND BARONY OF SCRIVELSBY I.E. HORNCASTLE
MAPLEBUSH UNDER SHERWOOD · ELLMERE PIT · NEWHAM MERE END · FILWARD MERE · MERE MOUTH
course of Newham drain
STIKNEY
BARONY OF HORNCASTLE & SCRIVELSBY
VACCARIA OF REVESBY, FORMERLY MOORHOUSE, NOW COWHOUSE.
VACCARIA CALLED CUSTOMHOUSES
LANGWORTH
HUNDLEHOUSES
NEWHAM
SWINECOTES
SIBSEY
WILLOWS
THESE FIVE VACCARIA BELONG TO KIRKSTEAD
KIRK-STEAD
HERMITAGE
MERE BOOTH
RIVER WITHAM

FIGURE 321—*The Kirkstead Abbey Psalter map of cow-pastures* (vaccariae) *north of Boston, Lincs.* c *1300.*

One of the earliest reasonably accurate medieval plans is of the water-works at Canterbury Cathedral of about 1165 (vol II, figure 628). Such plans are engineers' drawings rather than surveys proper. The first true survey map—from England at least—is that drawn up about 1300 on account of a boundary dispute between two baronies (figure 321). It shows the boundary running along a ditch leading into the river Witham, with five cow pastures (*vaccariae*) to the west belonging to one barony and four on the east belonging to the other. The boundary is marked by a shield on a pole which the commission of true and sworn men set up at the beginning and the end of their survey-walk. All the *vaccariae* may be identified from villages and houses marked on the modern map. The boundary still exists, but the medieval map straightens the course of the river. The distances on the map are tolerably accurate, but the angles follow the bending of the river.

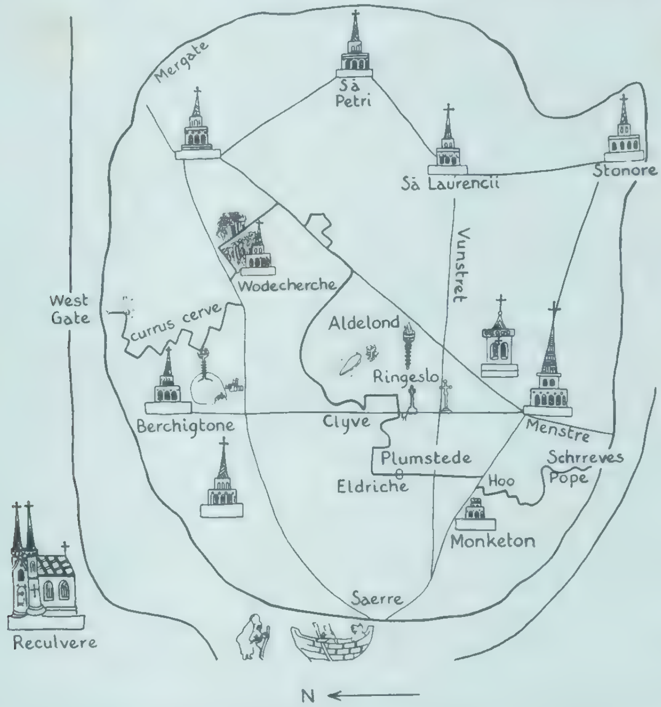

FIGURE 322—*Map of the Isle of Thanet, c 1414. The modern forms of the place-names are easily recognizable: thus Alland* (Aldelond), *Birchington* (Berchigtone), *Oldridge* (Eldriche), *etc.*

A map of the Isle of Thanet of about 1414 (figure 322) shows how greatly topographical surveying technique had improved towards the end of the Middle Ages. But despite greater detail and pictorial representation of various buildings it still shows considerable angular distortion, and the 'island' is almost square instead of having its length nearly twice its breadth.

It is interesting to compare the features of these topographical maps with those of the navigation-charts, which were drawn with the aid of the magnetic compass. The charts, unlike the maps, render angles of bearings more accurately than distances. Both types were transformed, or rather united, after the development of angle-measuring devices and triangulation-techniques which became necessary in Britain and elsewhere with the sixteenth-century redistribution of the church lands following the Reformation, and with the new geographical knowledge brought by maritime explorations.

VIII. THE WIND-ROSE AND THE CARDINAL POINTS

For survey, cartography, and navigation alike, the underlying techniques rest on a clear understanding of the meaning and measurement of distance and direction, which together establish position. For some purposes, such as drawing a plan or defining a coastwise sailing-route, the correct representation of relative position suffices, but a true map must also show absolute position on the globe. This requires astronomical observations, and the use of a system of terrestrial co-ordinates—parallels and meridians—such as those of Ptolemy.

The decline in the study of astronomy and geography in the Latin world after the separation of the eastern from the western Empire, together with the barbarian invasions, made neglect of such works as Ptolemy's inevitable. Cartography became limited to what may be termed sketch-maps. These were not drawn to scale and were often highly diagrammatic or stylized.

Apart from the Roman mile (1000 paces each of 5 common feet), measures of distance were ill defined, while direction was not precisely determined. It is true that mathematicians since Hipparchus (fl 130 B.C.) had divided the circle of the horizon into degrees, but the layman merely recognized the four quarters of the sky, related to the daily journey of the Sun. The Greeks, however, had early distinguished and used the directions of summer and winter sunrise and sunset, while sailors had given individual names to the most important wind-directions between the four cardinal points.

A scheme which gave to each of the cardinal points two companions had finally evolved as a twelve-fold wind-system or wind-rose. This was current in classical literature, but there was also an eight-fold system mentioned by Pliny, which was probably that used by sailors. It is beautifully illustrated by the octagonal Tower of the Winds at Athens, of the second century B.C. (plate 26 A).

The Germanic peoples who lived in lands where winds were less regular named their winds only from the four cardinal points. When the need arose for indicating intermediate directions they spoke of 'north and east', 'south and west', and so on. These were not thought of as 'points', but as quarters of the sky. The 'and' became elided and we find, for example, Alfred the Great (871–99) using the terms *northan-eastan*, *southan-eastan* in his translation of the work of Orosius (fifth century A.D.).

It seems likely that there was no further subdivision until the introduction of the magnetic needle in the twelfth century, for only then do we find the terminology that by combinations of the eight wind-names used in the Mediterranean, or of the existing eight compound names of the Germanic languages, gave sixteen-fold and thirty-two-fold systems. Even the thirty-two 'points' or wind-rhumbs had a play of nearly six degrees on either hand, although seamen gradually came to recognize half- and quarter-points.

IX. MEDIEVAL VIEWS ON THE HABITABLE WORLD

The astronomer or the maker of sun-dials could, of course, establish his meridian by the traditional method, that is by marking the position of a pair of forenoon and afternoon shadows of the upright gnomon which had equal length, and bisecting the angle between them. But such knowledge was rare and its application rarer—at sea it was impossible—so that the measurement of direction, like the measurement of distance, remained imprecise. The medieval cartographer therefore did not hesitate to adapt the shape and size of his map, and the position of its particular parts, to the piece of parchment that he was using, or to give prominence, by enlargement, to particular features. The actual shape that he gave to the *mappa mundi*, the world-map, was also a matter of taste. Thus the eccentricities and humours—as they seem to us—of such maps do not carry the implications often nowadays assigned to them. The Christian maps, in fact, were based on those current in the pagan Roman world, and particularly on those accompanying late Latin textbooks, while the general principles of ancient classical geography were accepted.

It is an error to suppose that educated people in the Middle Ages thought the Earth flat. Indeed, the basic fact for the initiated was that the Earth was a sphere, a mere point by comparison with the universe, which itself was bounded by the ever-turning starry firmament. Only one-quarter of the sphere of the Earth was known, and was often itself briefly called 'the Earth'. It comprised three parts, Asia, Africa, and Europe, completely surrounded by the ocean. The suggestion of Crates the Grammarian (*c* 165 B.C.) was accepted, that it was reasonable to suppose that the three unknown quarters of the globe resembled the known, consisting of inhabited land-masses surrounded by ocean. The people of the southern quarter opposite our own would be 'foot against foot', literally antipodes, to ourselves. There would be an equatorial ocean right round the zone held to be 'unhabitable because of the heat', so that the two southern continental masses could never be reached from ours.

This last point was seized on by St Augustine (354–430) to prove that there could not be antipodes, for it had been promised that the gospel should be preached to 'all men'. The later change in the meaning of antipodes, from a human race to a position on the globe, has here confused an issue and perhaps did so from the first. St Augustine did not reject the spherical shape of the Earth. That matter, however, was deemed to concern the astronomer and geometer only, not the geographer and still less the ordinary reader. Thus it was passed over with but slight mention by the Christian encyclopaedists, as for example by St Isidore (? 560–636) in his famous *Etymologiarum libri VII*.

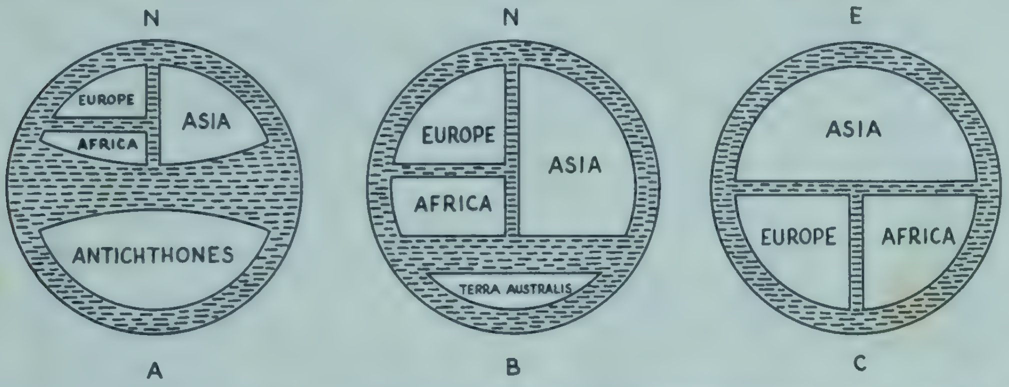

FIGURE 323—*Three types of medieval world map.* (A) *The known hemisphere with two balanced land-masses;* (B) *the* terra australis *has become residual;* (C) *the* Ⓣ *map showing only the known habitable world.*

There are three early types of world map: one type gives the whole eastern hemisphere with its pair of known and unknown continents; another shows merely a residual *terra australis*; the third is limited to the known habitable world, variously presented as lenticular, rectangular, oval, or circular (figure 323).

The three-fold division of the world into Asia, Africa, and Europe was effected by the rivers Tanais (Don) and Nile and the Mediterranean Sea, which were stylized into a T of water, giving the well-known OT or Ⓣ map (figure 323 C) after the surrounding ocean had been added. Christian features and symbols were gradually added to this *mappa mundi*, and the orientation was changed so that the east (usually marked by the 'Earthly Paradise') was at the top. As the copying and decoration were entrusted to monastic or professional illuminators, a map was usually embellished with pictures and lively ornaments, especially in large wall-maps, such as the Hereford map (figure 324), intended for royal or ecclesiastical chambers. That many who looked at them, even many who drew them, believed the circle of the habitable world to be the whole world and to be flat, is undoubtedly the case, but the learned clerical world, which had some grasp of mathematics and astronomy, did not lose sight of the truth.

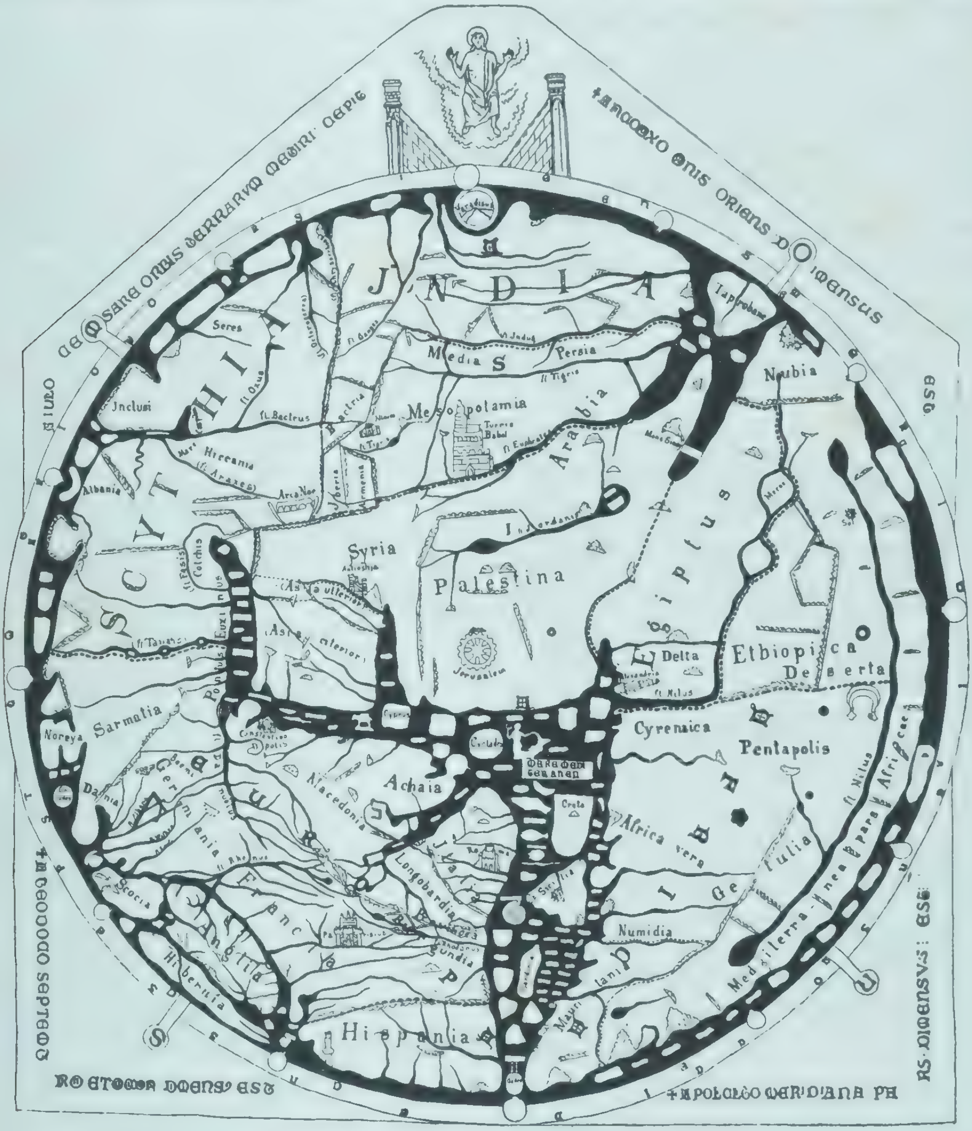

FIGURE 324—*The Hereford* mappa mundi, *much simplified. Jerusalem is at the centre, and the East at the top. c 1280.*

X. MEDIEVAL CARTOGRAPHY

Meanwhile, Greek geometry and astronomy continued to be studied in the eastern Empire, and the leading works were translated into Syriac, or made the subject of compilations in that language. Such, for example, was the oldest surviving treatise on the astrolabe (ch 22), written by Severus Sēbōkht (d 667). The Arab conquest of Mesopotamia, Syria, and Egypt led to the translation of Greek science into Arabic, and to the setting up of libraries and observatories such as those ordered by Al-Ma'mūn (Caliph 813–33) at Baghdad and Palmyra. Learned Muslims and Jews remained settled in the cities of Spain and Sicily after their reconquest by Christendom, and these centres of learning were the principal agencies through which Latin translations of scientific texts were diffused in the western Christian world.

Even more important from the standpoint of technology was the passage to the Latin west of old and new mathematical instruments and tables and, for our immediate purpose, their influence on map-making. The direct Islamic contributions to cartography included modification of the world-map, remeasurement of an arc of the meridian, and compilation of new tables of latitude and longitude. Using the back of the astrolabe the Muslims could determine latitude with precision by taking the mean of the upper and lower meridian-transits of a bright star, or by the noon altitude and tabled declination of the Sun. For longitude they compared the local times of lunar eclipses, using a water-clock.

Since Arabs were settled along the East African coast as far south as Sofala, and traded in the Sudan, they followed Ptolemy in extending the habitable world across the equator, and in placing the lake sources of the Nile in the equatorial region. Their superior practical knowledge also allowed them to open the Indian Ocean towards the Far East, where Ptolemy had closed it (figure 312). They were quite familiar with the idea of a spherical earth, but they were satisfied to sweep a circumambient ocean about the inhabited world as they conceived it, and to place the whole in a circular frame. Their tables of latitude and longitude were used only for astronomical purposes, and covered 90° E and W of an imaginary city (or island) of Aryn, the cupola of the world on the zero meridian and on the equator, treated much as we do the longitude of Greenwich. For convenience, however, the prime meridian was transferred to a point $72\frac{1}{2}$° W, supposed to be the 'farthest inhabited west', as opposed to the 'true west' in 90°. The earliest tables, those of Ibn al-Zarqālī (known to the Latins as Arzarchel) were compiled at Toledo in the early twelfth century, and translated into Latin later in the same century by Gerard of Cremona (1114?–87). The tables reckoned Toledo as at 11° E, or $28\frac{1}{2}$° from the 'true west'.

The effect of the impact of the restored Greek and new Arabic learning is well illustrated by the geographical section of Roger Bacon's *Opus Majus* (1264).

Here he points out how much information can be deduced from the latitude of a city or region, and for the first time since Ptolemy he attempts a map in which position is fixed by co-ordinates, although he laments the paucity of data 'among the Latins'. His parallels are set out as straight lines parallel to the equator and at their correct distances as taken from the graduated brass meridian on a globe. They were apparently not chosen at equal intervals, but so as to run through particular cities, where they were intersected by the appropriate meridians, running from the equator to the pole. A red circle round the point of intersection showed the precise position of the city, in striking contrast to their indication by large and vaguely placed vignettes on the ordinary *mappa mundi.*

This map of Bacon's, which he sent to Pope Clement IV, is lost. We know, however, that he considered the general distribution of land and water, and rejected the idea of four 'quarters' in favour of a single land-mass. This stretched eastward so far that, as Aristotle had suggested, the Atlantic Ocean between the confines of Spain and of India was comparatively narrow and might easily be crossed. Bacon also believed, on literary evidence, that both India and Ethiopia extended southwards far across the equator (with a large gulf between them). Nevertheless, the generalization about the five zones, of which the torrid and the frigid were not habitable, was to hold the field in geography textbooks down to the sixteenth century.

The Arab measurement of the circumference of the Earth had been described by Al-Farghānī (Alfraganus of the Latins, fl 861) from whom Bacon takes it. The elevation of the pole star, which (with due attention to its eccentricity) gives the latitude, was taken by Al-Farghānī near Palmyra, by means of an astrolabe or quadrant, and the observers then followed the meridian until their instruments showed that they had moved one degree. This distance was measured and was expressed, says Roger, in great cubits. If so, it works out at 68 miles, which is very close to the truth; but it was generally treated as from the lesser cubit, giving a result of only 56⅔ miles. When it is recalled that Ptolemy's figure of 500 stades or 62½ Roman miles had been recovered, and that the widely current degree of Eratosthenes of 700 stades (p 506) was reckoned by St Isidore and others at 87½ miles, it is easy to imagine the resulting confusion. The resolution of this confusion was, as yet, no one's business or interest. Moreover, the existence of a 'geometrical' mile of 1000 'geometrical' feet, which measured five-sixths of the common feet of the Roman mile, was quite overlooked. Campano da Novara (thirteenth century) stated that 81 'geometrical' miles went to a degree, and this short mile corresponds closely to the 'little sea mile' which was used on the medieval maritime charts of the Mediterranean Sea.

XI. NAVIGATION-INSTRUMENTS

Meanwhile the detail of the world-map was being improved from two sources —the travel of Europeans across the vast Mongol Empire, and the introduction of the sea-chart. At some time in the twelfth century, and possibly earlier, there was discovered the directive property of the lodestone, of which the attractive property had long been familiar. A needle or steel wire which had been rubbed by the stone would, if floated in water, turn towards the pole star. From the days of the Phoenicians—perhaps even of the Minoans—the sailor had steered at night by the northern constellation of the Lesser Bear, and during the day by the course of the Sun. When the sky was overcast he lost his bearings. Now he could recover them by setting the 'touched' needle afloat on a piece of cork or straw.

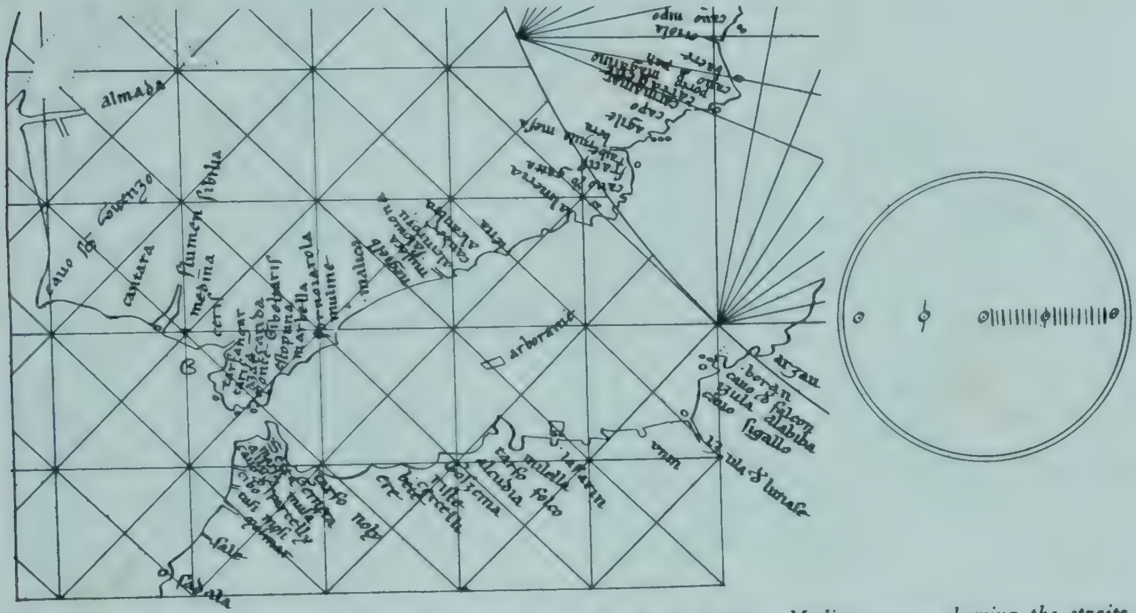

FIGURE 325—*The* Carte Pisane, c *1275*. (Left) *A portion of the western Mediterranean, showing the straits of Gibraltar and the Spanish and N. African coasts, with the network of 100-mile squares and diagonals used for transferring detail, and found outside the rhumb-line circles* (upper right); (right) *the scale of the map: each large division is 50 miles, each small division 5 miles.*

At first the navigator did no more than this, but by about 1180 Alexander Neckam appears to describe a pivoted needle, and during the first half of the next century we find that the nomenclature of the wind-rose now covers thirty-two points. Sailing-directions, traditionally stated in terms of distance and following wind, could thus take on a new precision, and an accurate chart could be drawn. Such a chart, covering the Mediterranean and Black Seas, survives from about 1275, and it is so detailed, accurate, and stylized that it must certainly have had predecessors (figure 325, the *Carte Pisane*). It carries a scale, being the oldest map to do so, and is drawn upon a set pattern of wind-roses (figure 326), providing a network of rays or rhumbs by which a pilot, furnished with dividers and ruler, could set course between any two ports assigned.

The term 'sailor's compass' originally meant the division of the horizon by the wind-rose, and a compass-card was at first used side by side with the bare floated or pivoted needle. Once the needle was attached beneath the card, which was perhaps done at the beginning of the fourteenth century, the simple magnetic compass was complete. A contemporary, friend, and teacher of Roger Bacon's, Peter Peregrinus of Maricourt in Picardy, had actually described two boxed compasses in 1269, a floating one containing a lodestone, the other with a pivoted needle. These had scales of degrees marked on their respective lids, and were intended for establishing the meridian for astronomical purposes. That no such use is later reported suggests that the variation of the needle had been discovered—it was certainly known and allowed for early in the fifteenth century by the makers of travellers' sun-dials (figure 354), and possibly also by Flemish compass-makers.

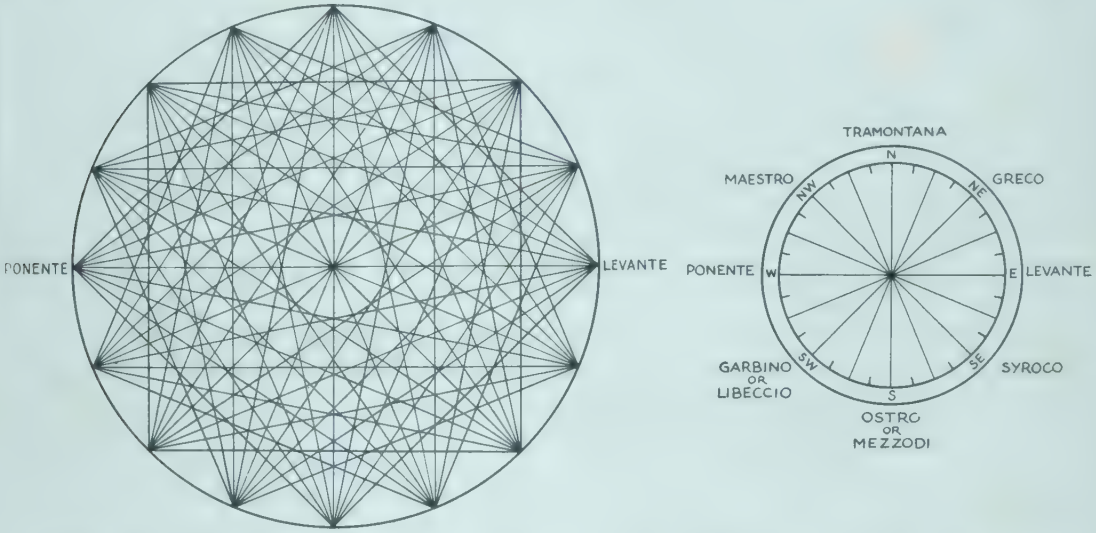

FIGURE 326—(Left) *Scheme of rhumb-lines connecting a wind-rose divided into sixteen points with as many others similarly divided. The* Carte Pisane *was drawn over a pair of such circles;* (right) *the Italian division of the compass or wind-rose into 32 quarters or points.*

By about 1298, Marco Polo (1254?–?1324) had given an extensive description of China and even of Japan (placed by a misunderstanding 1500 miles from the mainland), as well as of the East Indies. The fourteenth century saw the incorporation of the Mediterranean sea-chart in the *mappa mundi*. In the famous 'Catalan Atlas' of 1375 we find evidence of a widening topographical knowledge —of the Atlantic islands, for example, of the negro kingdoms beyond the Sahara, and of the Far East (figure 327). It is in this 'Catalan Atlas' that we first meet with a tidal diagram, giving the 'establishment of the port' for a number of Breton and English Channel harbours. These are set out on the rays of a compass or wind-rose, for sailors reckoned hours and days by the thirty-two points, assuming (incorrectly) that the heavenly bodies moved through equal azimuths in equal times—that is, they ignored the obliquity of the local horizon. Supposing, for example, that full sea at a particular port occurred three hours after the new moon crossed the meridian, they would say 'Moon NE—SW full sea' and mark the port on the appropriate rhumb. The second high tide of the day would occur 12 hours later, that is, on the south-west rhumb, and low tides on the south-east

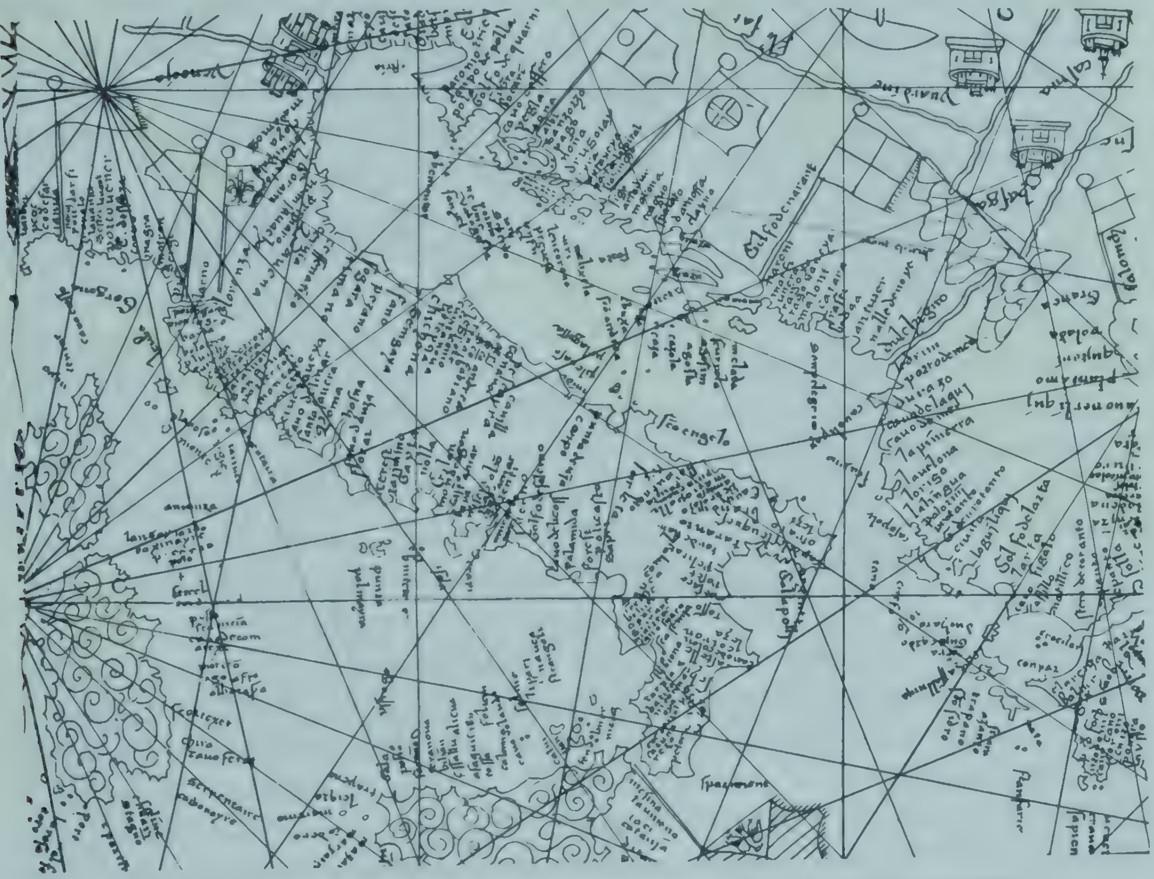

FIGURE 327—*The 'Catalan Atlas', 1375; a portion showing Italy, the Adriatic, and Sicily.*

and north-west rhumbs. The daily retardation was reckoned at forty-five minutes, or one point on the thirty-two point wind-rose. Hence if the age of the moon was known, the time or rhumb of high tide could be found by the card.

While the seamen of the west and north-west of Europe learnt to make and use tide-diagrams, they had no charts such as were used by the presumably better educated Mediterranean pilots. Sailing-directions, called in English rutters (French, *routier*) and in Italian *portolani*, were common to both, and besides courses these recorded land-marks, rocks, shoals, tide-rips, and dangers generally. Once he found himself in soundings the medieval sailor made use of lead and line, the lead greased to bring up a revealing sample of bottom deposit, as had already been the case in the days of Herodotus (fifth century B.C.).

In addition to magnetic compass, and lead and line, a sand-glass was essential to the navigator. This was to set the watch, and two-hour or 'half-watch' glasses seem to have been in use. Alphonso the Wise (king of Castile, 1252–84) had ordered that all Spanish ships should also carry an astrolabe or quadrant, to read the latitude. This could have been done only very exceptionally, for suitable types of these instruments were not invented until the fifteenth century, the age of oceanic discovery (ch 22). During the fifteenth century, however, we find Italian tables for reckoning the 'course made good', that is to say, the resultant distance sailed in the required direction when the ship has been obliged to tack. This was not worked out in terms of northing and easting as in modern sailing, since latitude and longitude were not plotted on the medieval chart.

The earliest description of the method is to be found in a long memorandum[1] on shipping matters addressed to the Captain-General of Venice in 1428. But as it is referred to very plainly by Ramón Lull (for example, in answer to question 192 in his *Arbor Scientiae*) before 1295, it must date back to the early days of navigation by compass and chart. This gives the method interest and importance, since it involves trigonometrical resolution of triangles, not merely in the mathematician's study, but in the ordinary daily practice of the professional pilot.

The use of the scale-drawn chart and of the Rule and Tables of *Marteloio*, as the method was called, stamp the Italian seaman as the first technician to make use of applied geometry. The academic mathematician had, however, to adapt the Rules to the probable limitations of the user's aptitude and knowledge. The sailor recognized angles only as 'quarters' of the wind, which ran from one to eight between each of the four cardinals, and therefore contained 11° 15′, 22° 30′, 33° 45′, and so on up to 90°, which were tabulated as one-quarter, two-quarters, and so on up to eight-quarters. Four such quarters made a 'wind' on the Italian eight-fold wind-rose (figure 326). An Englishman would call them rhumbs or 'points'.

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[1] Egerton MS 73, British Museum.

A knowledge of multiplication and division was sufficient for the user of the tables, which were arranged so as to answer questions of the following two types. First, 'I wish to sail on (say) the east rhumb, but contrary winds oblige me to sail one quarter (or two, or three, etc) south of east. When I have sailed 100 miles how far have I gone to the east, and how far am I off my course?' The first table sets out the answer in three columns, number of quarters, distance on true course, distance off course. Secondly, the pilot asks: 'I am 10 miles off my true course which is (say) east. How many miles must I sail, and at what distance east shall I meet it, if I turn towards it one (two, three, . . .) quarter(s)?' The required figures are found in the second table. In the memorandum of 1428, to which we have just referred, there are worked examples that show how to proceed when the actual figures are other than the 100 miles or 10 miles to which the tables correspond, but it is difficult to judge what proportion of pilots would have the necessary command of arithmetic. A diagram called 'The Circle and Square', that accompanies the memorandum but is not explained, suggests that

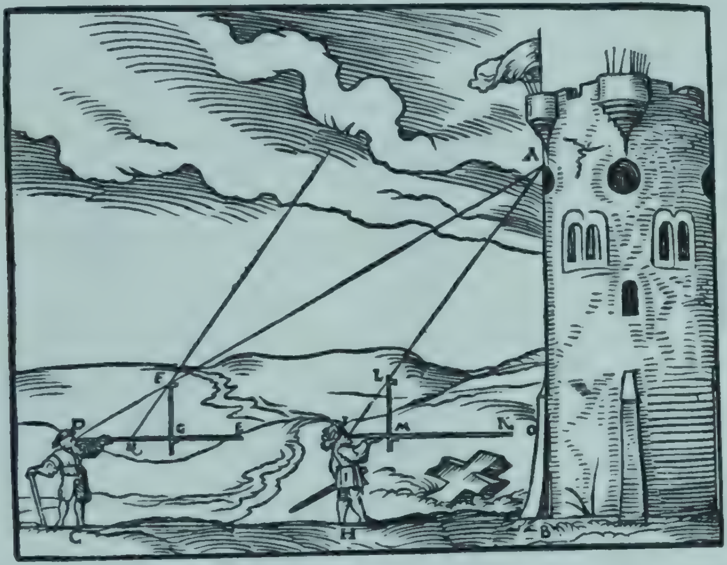

FIGURE 328—*One method of using the cross-staff to measure inaccessible heights. At the nearer position the transom is adjusted so that its distance from the eye is equal to half its length, at the farther position so that its distance from the eye equals its length. Then (since the tangents of the angles subtended are 1 and 0·5 respectively) the height is equal to the distance between the two positions, added to the height of the observer's eye. For this method to be accurate the height must be vertical, both positions on a horizontal plane, and the cross-staff held horizontally.*

a graphical method of solution was also current, for which a quite simple rule would be adequate.

An instrument that was to come into general use among mariners in the sixteenth century was first described by the Provençal Jewish mathematician, Levi ben Gerson, in 1342. This was the cross-staff, designed at first for the use of astronomers and later known as 'Jacob's staff' (p 546 and figure 340). The cross-staff could also be used for geometrical survey, that is, for finding heights and distances by the method of similar triangles, a commonplace of Greek geometry that was beginning to reappear in Latin dress for western use in the twelfth century. Again the principle was simple (figure 328). An astrolabe, quadrant, or geometrical square, or even a measured staff, could be employed instead of a cross-staff, and as there were no tables of tangents a graphical device, the *umbra recta et versa*, was in use to find the required ratios (figure 329).[1] Actually, however, these methods appear to have been used in medieval days for geometrical demonstration only and not for any practical purpose. There is little evidence of precise survey taking place, land-areas being reckoned to the nearest acre (or half-acre) after rough measurement with a perch rod. On the other hand, the erection of large buildings, such as castles, cathedrals, and forts, and the laying-out of new towns could hardly have been done without some preliminary survey.

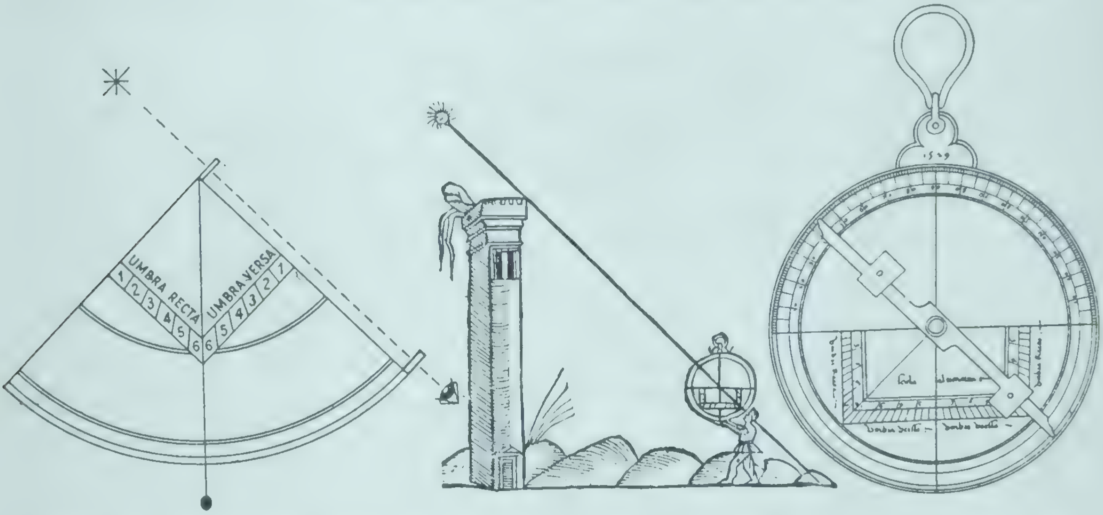

FIGURE 329—*Shadow-scales* (umbra recta *and* umbra versa) *on a quadrant* (left), *on the* dorsum *of an astrolabe* (right), *and shown in use in a work of 1564* (centre).

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[1] A graduated square with six or sometimes twelve divisions was drawn on the quadrant, a double square on the back of the astrolabe (figure 329), which gave the ratios $\frac{1}{6}$, $\frac{2}{6}$...$\frac{6}{6}$ (along the side) followed by $\frac{6}{5}$, $\frac{6}{4}$, $\frac{6}{3}$...$\frac{6}{1}$ (along the bottom), i.e. the figures on the scale are to be put over 6 up to an angle of 45 , and under 6 for the larger angles of elevation..

We read that the Arabic writer Messahala of Basra, who wrote on the astrolabe, took part in surveying the site for the foundation of Baghdad in A.D. 762–3.

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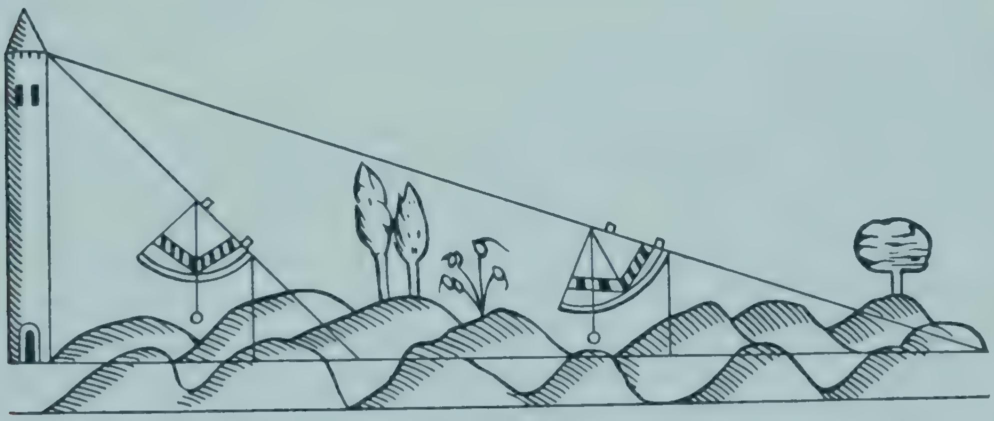

Measuring heights and distances with the shadow-square on the reverse of a quadrant.

20

CARTOGRAPHY, SURVEY, AND NAVIGATION 1400–1750

E. G. R. TAYLOR

I. CARTOGRAPHY

THE pressure of Turkish armies upon the eastern Mediterranean lands during the opening decades of the fifteenth century had among its lesser consequences the stimulation of new techniques in the fields of cartography, survey, and navigation. For the Greek manuscripts brought by Byzantine scholars into Italy included Ptolemy's 'Geography', which introduced new ideas of what a map should be, while the enforced diversion of attention towards western trade-routes demanded new methods of navigation and new maritime charts suited to the conquest of an ocean.

The text of the Alexandrine astronomer's *Geographike Syntaxis* (pp 502, 509), although known to the Arabs, had never reached the Christian world and was translated into Latin for the first time in 1409 by Jacobus Angelus. From that date the old circular *mappa mundi* (figure 324) was doomed to disappear. Nevertheless, it lingered on until printing made the new type of world-map familiar, and, indeed, a splendid example was drawn in 1459 by Fra Mauro, a copy of which was sent to the king of Portugal at his own request. Among the materials that the Venetian cartographer made use of were a well drawn Mediterranean sea-chart, charts of the new Portuguese discoveries along the African coast, and much surprising detail about the topography of Abyssinia and eastern Africa. Yet, encyclopaedic as it was, his map was still no more than a sketch-map, one drawn, that is to say, without reference to the mathematics of the globe, but only to an immensely extended horizon.

Projections. A true map must indicate the precise position of each feature upon the sphere of the Earth, and consequently the mutual distances and directions between them. Ptolemy had demonstrated in the second century A.D. how this could be done by means of a system of co-ordinates—the parallels and meridians—assumed upon the globe and mathematically projected upon a plane surface. But whereas celestial co-ordinates for a hemisphere of the stars can be determined by an astronomer from a single point, he can observe the terrestrial co-ordinates only of the place where he stands. Nevertheless, if the length of a degree of a great circle of the globe is known, any measure or estimate of direction and distance can be transformed into latitude and longitude. This laborious calculation was carried out by Ptolemy for all the features of the known world, and from the resulting lists of figures his maps were drawn—*ipso facto* to scale. As previously mentioned (p 503), his original maps have not survived, but they can be and have been redrawn from his data.

Taking 500 stades as the measure of the degree, he devised two plane projections of the spherical co-ordinates for his 'universal' or world map, and these laid the foundation of modern cartography (p 509). The prime meridian on the terrestrial globe must be arbitrarily chosen, and Ptolemy made his calculations relatively to Alexandria. For convenience, however, he numbered the meridians from the farthest known west to the farthest east, so that longitude zero ran through the Fortunate Islands. The Renaissance reader interpreted these as the Canaries, and the prime meridian was taken as running through the most westerly island, namely Ferro.

Later theories about the variation of the compass led to the idea that there was a 'true meridian' of no variation. During the sixteenth century, therefore, many cartographers took this as the prime meridian, assuming that it ran through St Michael Island in the Azores. During the seventeenth century, when observatories were founded in Paris and London, a new practice began of using the meridian of the capital city as the zero for national maps. There was no uniformity until the twentieth century.

The world-map to accompany Ptolemy's text is on his second projection. For maps of separate countries or regions he had written that it was sufficiently accurate to draw a rectangular grid, so long as the parallels were correctly spaced, while the meridians should be correctly spaced along the parallel half-way between the northern and southern edges of the map. Such a rectangular projection, which ignores the convergence of the meridians, distorts scale and distance most markedly in high latitudes—with which the Greeks were little concerned. Rather more than half a century after the 'Geography' was translated one of the most notable of the Renaissance copyists, the miniaturist Dominus Nicholaus Germanus (Donis), greatly improved upon it. This German monk came to work in Italy in 1462, and in the set of Ptolemy's maps that he drew for a noble patron in 1466 he substituted a trapezoidal projection for the rectangular one. This was effected quite simply. The northern and southern bounding-latitudes were each divided correctly and the meridians therefore converged. Both parallels and meridians were rectilinear.

Tabulae novae. The full influence of Ptolemy's text and maps was not felt until the printing-press gave them a wider circulation. The maps were first engraved for an Italian edition in 1477, and the set drawn by Dominus Nicholaus was used for the woodcuts in the Ulm edition of 1482. The great astronomer Johann Müller, generally called Regiomontanus (1436–76), had planned to issue an edition from his Nuremberg press, but his premature death prevented it. He had intended to include in this publication some *tabulae novae* or 'modern' maps drawn after Ptolemy's pattern, and in fact a number of such maps had already been devised. The earliest, so far as is known, had been commissioned by Cardinal Guillaume Filastre of Rheims, one of the first to possess a copy of the precious manuscript. The Alexandrine author had not known the Scandinavian countries, and it was to fill this gap in the contents of the Ptolemaic atlas that the cardinal called upon a Danish cartographer named Claudius Clausson Swart, usually known as Claudius Clavus (b 1388).

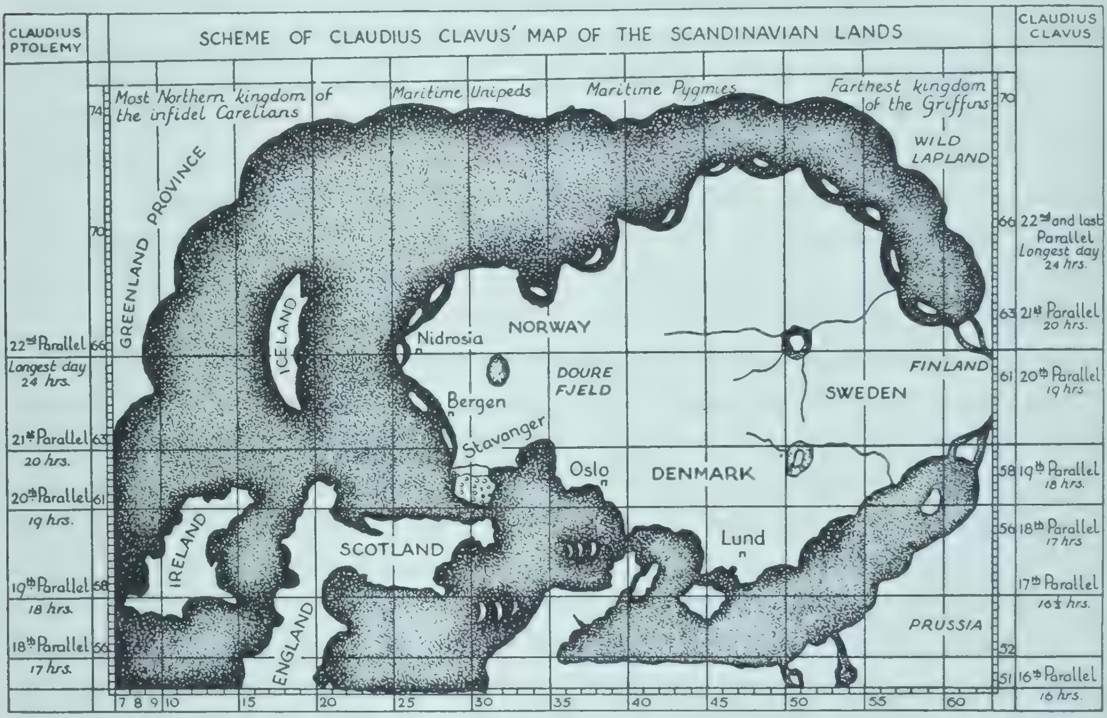

FIGURE 330—*Outline of Claudius Clavus's map of the Scandinavian lands, showing Ptolemy's latitudes* (left) *and his own* (right).

The map (figure 330) included the lands between the Baltic and Norway seas, and is remarkable for being extended to the west of Iceland so as to include the eastern shore of Greenland, a country thus mapped for the first time. The network was, of course, rectangular, and the meridians were correctly spaced along the sixtieth parallel, which was approximately the middle latitude. Following Ptolemy's practice, too, the 'climates' are distinguished in the margins, each defined by the length of the longest day. But the numbering of the parallels differs in the two margins, those on the left running from 55° upwards, those on the right from 51°. The former, the western margin, is headed Claudius Ptolemaeus, the latter Claudius Clavus. Clearly the Dane was correcting the Alexandrine master's figures: and the correction was a just one, for Scotland and Ireland, as copied from the Greek map, were too far north, and the new map was indubitably based upon an actual list of latitudes of Scandinavian towns. Among those accurately placed in this respect, some to within half a degree, are Nidrosia, Bergen, Stavanger, Oslo, Stockholm, and Lund. Yet the cartographer obviously had a very poor knowledge of the general lie of the land, and his longitudes are grossly erroneous. The extension of the Scandinavian peninsula is shown as from east to west instead of north to south, while the Gulf of Bothnia appears to have been unknown. A land-bridge runs from the east of the White Sea to Greenland, and along it are marked the Wild Lapps, griffins, pygmies, unipeds, and the infidel Carelians, names that indicate the vague literary and verbal descriptions on which the map-maker had chiefly to rely. Mountainous Scandinavia had no well travelled network of roads and navigable rivers such as, with the help of latitude-lists, facilitated the making of the *tabulae novae* of other western European countries.

Itineraries and river-systems afforded a framework for the first modern map of Germany, drawn about the middle of the century by Nicholas of Cusa (1401–64), cardinal and mathematician, who, like Filastre, possessed a manuscript copy of Ptolemy. Such great churchmen were among the most frequent travellers of the day, and among the most learned scholars.

As it happened, too, the early fifteenth century saw the introduction of a little instrument that allowed the traveller to determine, if he chose, the direction of each stage of his itinerary. This was the pocket sun-dial, the *organum viatorum* or 'travellers' instrument' made by a guild of the famous Nuremberg metal-workers, and set in the meridian by means of a tiny inset magnetic needle (figure 354). That these dials were early familiar outside Germany is indicated by a passing reference to *os relógios de agulha* ('clocks of the needle') in the *Leal Conselheiro* ('Faithful Adviser') written by King Duarte of Portugal between 1428 and 1437. While, however, the land-traveller thus equipped could draw a map, it is not until nearly the end of the fifteenth century that there is direct evidence of the association of compass-dial and cartography.

In 1492 Erhard Etzlaub, a compass-dial maker of Nuremberg, published a map of his native city and of its environs for sixty miles around. Seven or eight years later he followed this with a road-map, *Das Rom-Weg* ('The Road to Rome'), showing the routes across Germany to the Eternal City. Beneath the map is drawn a compass-dial, and the traveller is instructed to lay his own instrument correctly upon it and so find his way (figure 331). The influence of Ptolemy is shown here by the insertion of latitudes in the margin, as well as the lengths

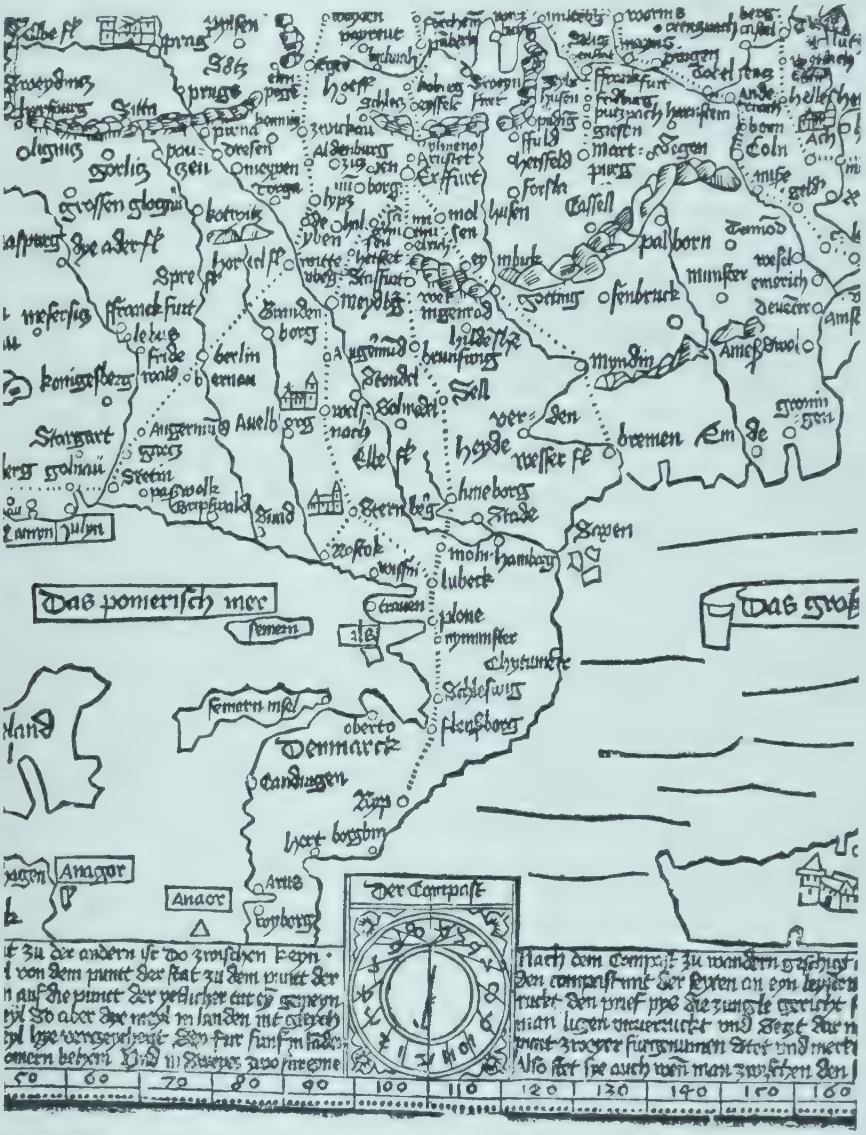

FIGURE 331—*Outline of the lower (northern) portion of Etzlaub's road-map. The scale is in German miles, and the roads are marked by dots spaced in miles. The compass-dial is to be placed as shown on the map, allowing for the NE declination of the needle.*

of the longest day, which defined the 'climate'. A new technical device was the representation of the roads by a series of dots placed one common German mile (four Roman miles) apart. Distances were thus immediately apparent. Towns were indicated by open circles, except for capital cities, which were represented by a group of buildings, and places of pilgrimage, where a church was drawn. Mountains were shown by chains or groups of mound-like hills, tinted stone-colour, and colour was also used to distinguish the nations and languages bordering on Germany. All this symbolism was explained in German in a leaflet sold with the map.

An itinerary map of Europe, also planned and explained as specifically for use with the traveller's pocket-dial, was published by Martin Waldseemüller[1] in 1511 and 1513. In 1525 and 1530 a printer and engraver of Augsburg, Georg Erlinger, published road-maps of the Holy Roman Empire, again showing the dial; these maps owed much to Etzlaub. By this date, the idea of a map as showing distance and direction correctly, as well as position on the globe, was thoroughly familiar.

Cosmography. A further impetus to the development of cartography was given by the work of Regiomontanus at Nuremberg in 1474–6, when he published the 'Alphonsine Tables' or *Ephemerides*, issued a calendar, and described the construction and use of astronomical instruments. His pupils and disciples were quickly able to advance the study of astronomy and cosmography at the universities; they published almanacs and extended the lists of latitudes and longitudes. To all this was added the stimulus of the sudden extension of the known world by the great discoveries made during the last decade of the century. Ptolemy's map projections had to be extended likewise. Contarini in 1506 and Ruysch in 1508 made use of modified versions of his conic projection, the latter cartographer, however, introducing the mathematical impossibility of placing the Pole at the vertex of the cone, which is inconsistent with the correct spacing of the parallels. Neither accepted Ptolemy's device for diminishing the latitudes south of the equator, but simply extended the cone. His second projection was developed by Johann Werner (1514) both in latitude and longitude, resulting in a heart-shaped world-map. The same writer made the more useful suggestion of employing the stereographic projection (long known to astronomers) in cartography. This is a true geometrical projection of a hemisphere from an opposite point on the equator or from one pole. A simple modification of it is to divide the central meridian, the equator, and the bounding meridian of each hemisphere

[1] Waldseemüller (*c* 1470–*c* 1518), latinized as Hylacomylus, is credited with being the first to call the New World *America*, in his *Cosmographiae Introductio* (1507).

correctly (that is, equally) and pass arcs of circles between the three points thus obtained (figure 332). This is the globular projection. Waldseemüller in 1506 drew a world-map in which the lines of latitude were parallel straight lines correctly spaced. Each was equally, but not correctly, divided by the curved meridians, since the author wished to diminish the true convergence. In fact the ingenuity of mathematicians can devise an infinity of projections, each producing its own slight distortions, but the first significant novelty was the network for a marine chart invented by Gerard Mercator in 1569 (p 550).

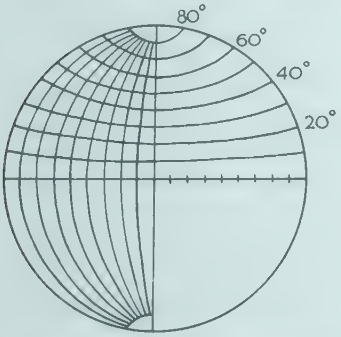

FIGURE 332—*Globular projection. The centre meridian and the circumference are divided into equal parts and the parallels are arcs of circles. The equator is also divided into equal parts, and the meridians are arcs of circles passing through the poles.*

The writings of the new cosmographers contained much that was immediately relevant to cartography, particularly the description of instruments, such as the astrolabe (p 603), quadrant, and astronomers' staff (soon to be adapted to survey, p 528) and the exposition of the mathematics of the globe. They furnished, for example, a detailed table of the diminishing length of the degree of longitude with increasing latitude, and gave a discussion of the measure of the arc of the meridian. Ptolemy's figure for this was naturally generally accepted; converted at 8 stades to the mile, it gave the length of the degree as 62½ miles. But German itineraries (as in Etzlaub's road-map, p 534) gave 15 German miles (equivalent to 60 'foreign' miles) to a degree; this figure found currency in Werner's commentary on Ptolemy (1514) and was subsequently adopted in France and England. It was recognized that the current mile differed in different countries, and that the measure of the stade was uncertain. Conversion tables gave, for example, 68 Italian miles to the degree, and sailors had their own figure (p 547).

The determination of the distance between two places whose latitude and longitude were known was a problem set out in the textbooks, and was at first solved (in Ptolemy's manner) by means of Pythagoras's theorem, assuming the difference in longitude and the difference in latitude as the lengths of the sides containing the right angle, the required distance being the hypotenuse. It was, however, pointed out by Stoeffler in his treatise *De usu astrolabii* (1512) that an error was introduced because the convergence of the meridians was ignored. He therefore substituted for the whole difference of longitude the difference measured along the middle latitude between the cities. This gives an approximately correct answer, but the error introduced by treating a spherical triangle as a plane triangle was not considered. Current textbooks supplied tables of squares and square-roots to assist in solving such problems as this.

II. SURVEY

While it is not until the opening of the sixteenth century that any direct evidence of cartographical surveying or discussion of the appropriate instruments can be found, the general principles had long been familiar to the medieval scholar. A section on the measurement of heights, depths, and distances was a normal adjunct to a treatise on geometry, but its purpose was rather to illustrate the properties of triangles than to persuade readers to take up field-work. The simplest proposition was that, knowing the angle of elevation of the top of a tower and its distance away, its height could be found by simple proportion from the geometrical square engraved (with an alidade at its centre) on the back of the astrolabe (p 528). The exercise could be carried out with a quadrant, or with a cross-staff, or even (using a little ingenuity) with a mirror or a simple rod. Then there was the device, by taking two observations, for finding the distance of an object that could not be reached, as for example a ship at sea (figure 333).

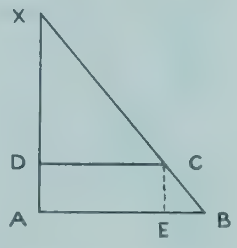

FIGURE 333—*Method of measuring distance to an inaccessible point* X *from* A. *The observer erects a mark at* A, *proceeds at right-angles to the line* AX *to* B, *marks it, goes directly towards* X *as far as any point* C, *marks it, and then walks to* D. *When* AB, CD, *and* AD *have been measured, then since* $AX:AB = CE:BE$ *the distance* $AX = \frac{AB.AD}{AB-CD}$.

Such a treatise on mensuration was to be found in the *Astrolabii Canones* of Robertus Anglicus, a thirteenth-century writer whose work was first printed about 1478 and reprinted many times subsequently. Twenty years before this, in a manuscript written and illustrated by a gun-founder for a noble patron, the same principles are to be seen related to the military art, for example to range-finding. Whether they were thus early applied in the field is, however, very doubtful. It is certain that the estate-surveyor, in drawing up his maps and terriers (pp 515, 540), long remained faithful to his perch-rod and simple estimates. Yet once printing made them familiar to practical men, these principles provided the actual basis of survey-, plan-, and map-drawing.

A surveyed regional map. Whatever may be surmised about the town-plans and modern maps that began to be published in the latter part of the fifteenth century, it can be quite definitely stated that systematic field-observations lay behind the chorographical or regional map of the upper Rhineland that appeared in the Strasbourg edition of Ptolemy in 1513. A representation of the earliest modern surveying-instrument had been published a year or two earlier in the

Strasbourg edition of a famous university textbook, the *Margarita philosophica*.

The same group of cosmographers and cartographers, Walter Lud, Ringman, and Waldseemüller, can be associated with both instrument and map. They were working at Saint-Dié in the Vosges Mountains under the patronage of Duke René II of Lorraine. The map of the Rhineland and another of Lorraine itself, drawn on a scale of about 1/500,000, were among twenty *tabulae novae* included in the Strasbourg Ptolemy; they are considered to be the work of Waldseemüller. The Rhineland map has been closely examined, and the latitudes of all the chief cities found correct to within 18′, while their mutual bearings, or angles of position, are also true within a few minutes of arc. Such accuracy could not have been achieved except by field-survey. The work, however, appears to have been done in two sections, the north and south halves of the map being faultily assembled.

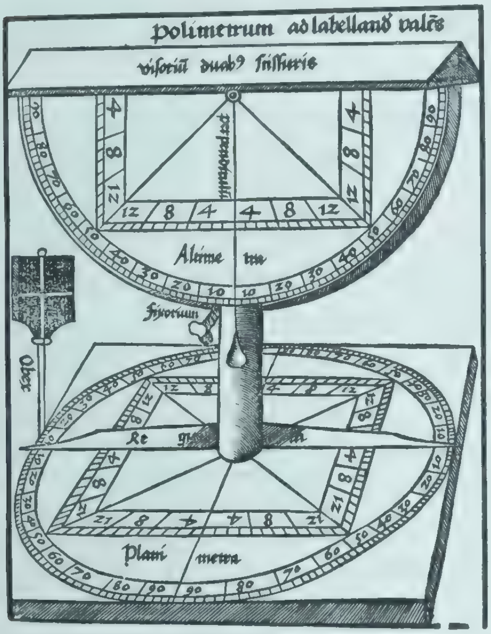

FIGURE 334—*Waldseemüller's* polimetrum, *from a woodcut of 1512. The sight is in the form of two crossed slits. The whole of the upper part of this levelling-instrument turns in the horizontal plane, with the index-reading on the lower scale. The upper part with the sights turns in the vertical plane and is read on the scale by the plumb-line.*

The polimetrum. The instrument referred to was known as a *polimetrum* (figure 334); it was designed for taking bearings and altitudes, and for levelling. It is found among addenda to the *Margarita philosophica* (which do not appear in the Basel editions) known to have been supplied by Waldseemüller. They include tracts on architecture and perspective. The author of the book, Gregor Reisch, was rector of Freiburg University, at which Waldseemüller had been a student. The first essential feature of the *polimetrum* is the sighting-tube, with twin slits, which turns in a vertical plane on a semicircular scale carrying a plumb-line. The tube can be clamped in a horizontal position by a screw, and then turned with its support in the horizontal plane, thus carrying a pointer or alidade around a horizontal scale furnished with an index. The fiducial line of the alidade corresponds to the line between the sighting-slits.

The whole instrument is the prototype of a theodolite. It was presumably oriented by means of a pocket compass-dial, such as Waldseemüller advised for use with his itinerary map. Such an instrument, or even a mere graduated circle and alidade, when carried up into church towers, could have been used for taking the horizontal angles of position plotted in the 1513 map of the Rhineland, which is also remarkable for the unusual fidelity of its physical features—particularly indicating the sharp, parallel edges of the rift-valley, which are scarcely apparent on much later maps.

Tartaglia's survey-instruments. It soon became customary for textbooks on practical mathematics to include one or more chapters on how to survey a region or country. Such a section is to be found in the *Quesiti e inventioni* of the Italian mathematician Niccolò Tartaglia (*c* 1500–57), which was first written about 1524 and published in an enlarged form more than twenty years later. Tartaglia describes two surveying-instruments to an English friend, both of them limited to taking horizontal angles of position and both embodying inset magnetic needles. The first had a large boxed needle in the centre of a circular graduated board or plate, the alidade being turned about on a collar fitted round the compass-box by a rod at right-angles to it. In the second instrument (which was cheaper) the alidade turned directly on a circular scale and the instrument was set by means of a needle from a little German compass-dial, inset at the edge of the board (figure 335). Latitudes, angles of position, and distances (taken from itineraries, from local knowledge, or actually paced) were still the basis of the map. Itinerary-distances were automatically reduced by one-quarter, to allow for the turns of the road. Ptolemy's practice was to deduct one-third from the length of reported routes before converting them to latitude and longitude figures.

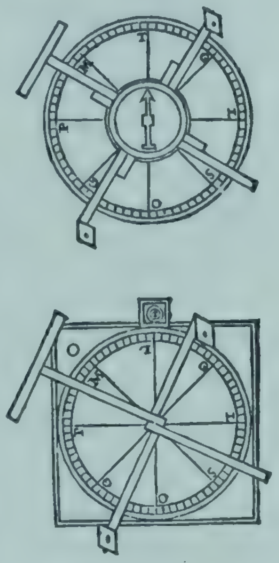

FIGURE 335—*Two surveying-instruments described by Tartaglia, 1546.*

Triangulation. In 1533 a notable technical advance was made in survey when Gemma Frisius (1508–55), professor of mathematics at Louvain, explained the principle of triangulation, which eliminated all distance-measurement save that of the base-line. The method involved taking angles of position, that is, bearings, of the same feature from either end of the chosen base-line. This line is then plotted to scale on paper, and rays to the object are ruled in at the correct angle from each end. The point at which the rays meet is the position of the object, and its distance can thus be measured on the scale of the base-line.

Simple as the procedure sounds, it is liable to many errors when applied in the field. Gemma recognized and emphasized, for example, the importance of the precise orientation of the instrument at either end of the base-line, and the need for placing it level, but his instrument was probably only the back-plate of his astrolabe, laid upon a parapet or a stool or stone. His nephew, Walter Arsenius, a notable instrument-maker, later made astrolabes with a little inset compass-needle under the ring, so that they could be used for taking such horizontal angles of position. Alternatively a simple graduated circular plate was used, fitted with an alidade, which had a small magnetic needle inset into the plate on the meridian line. These, too, were merely laid down on some convenient object, although they are also pictured in the latter half of the century mounted on a staff which could be thrust into the ground, or held upright.

Quite apart from errors of observation due to faulty placing of the instrument, errors in plotting must at first have been difficult to avoid. Drawing-instruments, for instance, did not include a protractor. The surveyor is directed to draw a graduated circle at either end of his plotted base-line and rule in the rays accordingly.

The plane-table (figure 338). A great advance in survey by triangulation followed the invention of the plane- (or plain-) table. It is first described in 1551 as the *holometre* by Abel Foullon, a member of the household of the French king (Henri II) and a student of mathematics. The essential feature of a plane-table survey is that the position-lines are ruled directly on a sheet of paper fastened to the table, as they are sighted. The modern sight-rule used in plane-table surveying is, as its name suggests, a well made ruler, engraved with plotting-scales and carrying sights. But in the earliest tables two sighting-rods were attached to the edge of the table, one of them moving to and fro along a scale so that it could be set and used for sighting from the second station at the end of the base-line, which had been directly marked off to scale. This was not a very satisfactory arrangement, and Foullon's table had the further disadvantage that it was set by a centrally placed compass-needle which could not be seen unless the paper were removed or torn open. However, a table shown in a contemporary edition of the *Cosmographia* of Sebastian Münster (1489–1552) is oriented by the customary little compass sun-dial, though, like Foullon's, it has the clumsy pair of attached sight-rods.

Drawing a plan or map by means of the plane-table was so simple a matter, since it required no mathematical knowledge, that surveyors, and in particular estate-surveyors, quickly became numerous. As a consequence, improvements were rapid. Well before the close of the century the separate sight-rule of modern type, with slit-and-wire sights, and carrying plotting-scales, was in use. The table had a frame which held down the sheet of paper; it was mounted on a tripod and oriented by a separate boxed needle. Moreover, the perch-rod, or the knotted rosined cord of the earlier 'land-meaters', had been replaced by a linked steel chain. The front 'chain-man', too, carried a bundle of arrows, to be thrust into the ground at each complete chain and picked up by the rear man, as is done today.

The theodolite. In 1571 the English mathematician Thomas Digges (*c* 1521–95) published under the title *Pantometria* the notes on mensuration written by his father Leonard Digges (d 1558), who had taught the subject in the middle of the century. The older man had given the name *theodelitus* to the bearing-dial, or circular plate with alidade (figure 336), and suggested its combination with another topographical instrument, the sight-rule turning on a vertical scale for measuring altitudes. The combined instrument (which was on the pattern of the early *polimetrum*) became known as the theodolite (figure 337). It was made in various patterns, such as that with a central inset compass on the lower plate, round which the upper part turned on a collar; but Digges left all detail to the 'skilfull artificer', only stipulating that there must be somewhere an inset needle, and that the variation (which he put at 11° 15′ E) must be noted. The instrument was mounted on a single leg or staff, and was to be levelled with a plumb-line. Both the vertical and horizontal plates were engraved with the geometrical square, as well as with a scale of degrees.

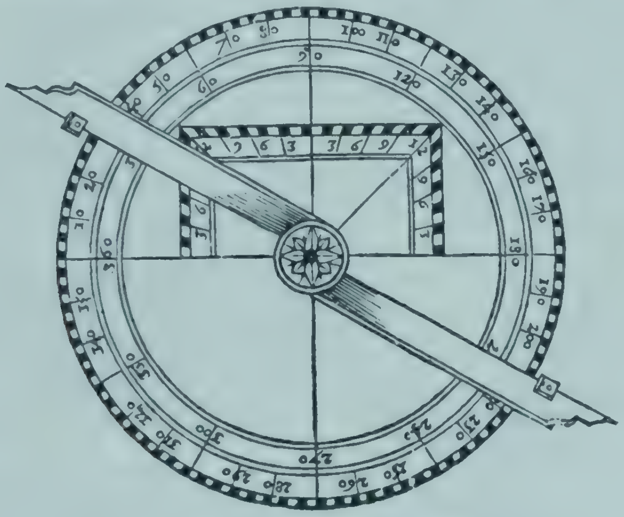

FIGURE 336—*Leonard Digges's 'theodelitus', 1571.*

Mathematical tables. The computation of the areas of fields and estates was a laborious matter for surveyors, who consequently were among the first to take advantage of mathematical devices that simplified their task. This is illustrated by the first comprehensive English textbook on survey, Aaron Rathborne's 'Surveyor' (1616), which can be taken as typical of professional practice from the turn of the century. The author advocates the new decimal arithmetic introduced by Simon Stevin (1548–1620) in 1585, and had himself designed and used a decimal chain. This was, however, shortly superseded by the more convenient chain of 100 links invented by Edmund Gunter (1581–1626) and still in use. Rathborne also made use of trigonometry, a subject on which a general textbook by a German writer had appeared in 1600. Pocket trigonometrical tables had now become available and, only two years after their invention, pocket-tables of logarithms, of which Rathborne writes enthusiastically. Not many years later Edmund Gunter put a logarithmic scale upon a staff, and 'Gunter's line', as it was termed, was employed for computation throughout the century side by side with the various slide-rules dating from about 1650.

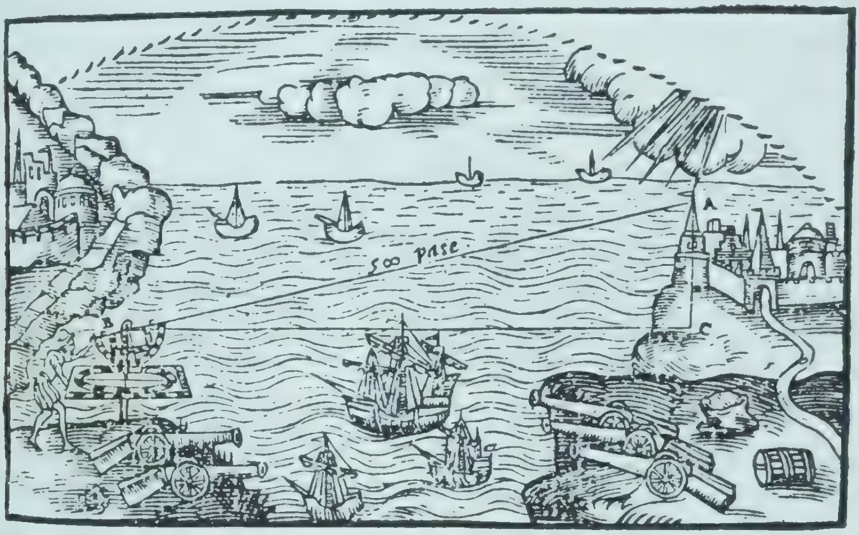

FIGURE 337—*The use of Digges's 'Topographical Instrument' (a precursor of the modern theodolite) to measure an inaccessible vertical distance. Assuming that by a method already described he found the distance* BA *to be 500 paces, he turns the sights of the instrument upon* A. *The perpendicular line falls on the tenth division of a linear scale of 120, i.e.* $\tan ABC = AC/BC = \frac{1}{12}$. *But* $AC^2 + BC^2 = BA^2 = 250\,000$ *paces. Hence* AC, *the required vertical distance, is* $\sqrt{\frac{250\,000}{145}}$, *which works out at nearly 42 paces.*

An engraving in Rathborne's book shows surveyors at work with theodolite and plane-table, their instruments mounted on tripods; readings are entered in an orderly manner in a field-book, and plotting is done with a protractor and a mounted needle for pricking points (figure 338). A bearing-dial or circle termed a 'circumferentor' is also in use, and the particular pattern described includes a table of horizontal equivalents (that is, reduction of slopes) on the alidade.

Levelling. An important part of survey had always been precise levelling, necessary in relation to water-supply, drainage works, and building. The Roman water-level or *chorobates* (p 511) was familiar in the sixteenth century through its representation in editions of Vitruvius's *Architectura* from 1486 onwards. The method employed was to sight horizontally forwards and backwards, either with a water-level or with a theodolite, on to graduated staffs held by assistants. Records remain of the survey made between 1609 and 1611 for the New River enterprise designed to bring water to London. This was carried out by Edward Wright (*c* 1558–1615), who combined mathematical learning with great practical experience, both in field-survey and in instrument-making. He went over the ground more than once, for, since the fall of level between Amwell and Islington averages only 5 in to the mile, great precision was demanded. According to a contemporary, Mark Ridley, Wright was accustomed to fasten a 'perspective glass' parallel to the sights of his instrument, and this would have assisted him.

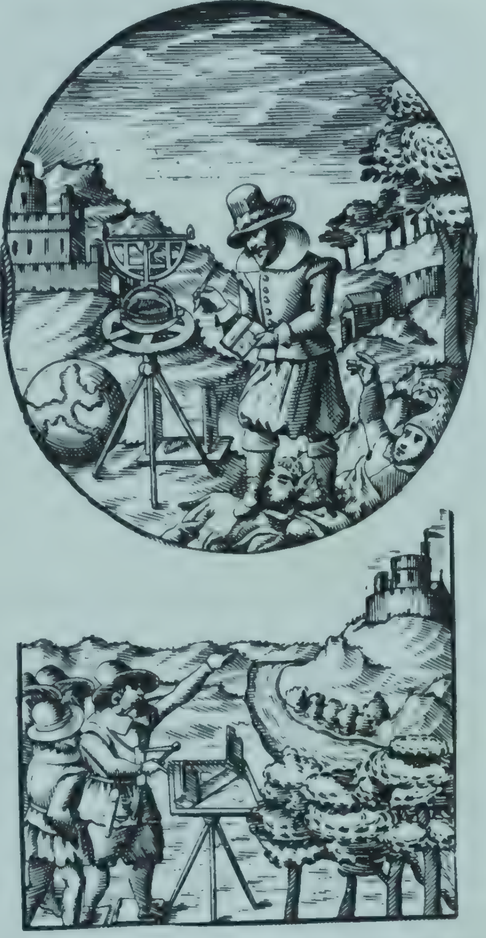

FIGURE 338—*Surveyors at work. Two vignettes from the title-page of Rathborne's 'Surveyor', 1616.*

The introduction into surveying-instruments of actual telescopic sights, carrying cross-hairs to define position, was the most important advance in survey-instrument making of the seventeenth century. In addition, the vernier (often miscalled the nonius) and the micrometer made fine measuring possible, while the bubble-level replaced the plummet. These improvements, however, were costly and were only slowly adopted, even by scientists. A treatise on levelling by the French savant Jean Picard (1620–82) describes the telescopic level which he used to survey the relations of the Seine and Loire, and other waters about Versailles; but he set his instrument with a plumb-line, as did his fellow Academicians Huygens (1629–95), Römer, and La Hire, who all designed somewhat similar levels.

The fact that the Torricellian tube or mercury barometer could give a measure of height was demonstrated by Pascal in 1648, but there are only sporadic experiments to record, such as those of John Caswell (1656–1712) and Edmond Halley (1656–1742), during the period under review.

The arc of the meridian. The French Academicians in 1669 first successfully attacked what is a fundamental problem of cartography, namely the precise length of the arc of the meridian. Willibrord Snell (1591–1626) had obtained an improved figure in 1606 by a triangulation carried out on the level plain of Holland, and Richard Norwood (*c* 1590–1675) got a surprisingly good result from his road-survey of the distance between London and York in 1635. Jean Picard and his assistants were able to adopt methods that inspired much greater confidence. Their base-line of over 11 000 yd was measured with extreme care by means of iron rods, and a system of 17 triangles covered the distance, about 70 miles, between Malvoisine and Amiens. The latitudes of the extreme stations, and of five intermediate points, were taken with a 10-ft quadrant, but it was realized that accuracy could be assumed only to the nearest two seconds of arc. The result accepted was 69 m 783 yd, in English measure. Some years later the triangulation along the same meridian was continued southward by Jean Dominique Cassini (1625–1712), and a rather higher figure was obtained; this gave rise to a controversy about the shape of the Earth which was not decided until the following century (p 553).

III. NAVIGATION

The methods of navigation developed first for the enclosed Mediterranean Sea and for the narrow seas on the continental shelf of north-western Europe (pp 523–9) were inadequate for the new ocean navigation of the early fifteenth century sponsored by the Portuguese Prince Henry the Navigator (1394–1460). The Canary Islands had been occupied in 1402, the Madeira group in 1420, and the Azores, due west of Lisbon, about 1444. All these island groups had already appeared on the fourteenth-century maritime charts, but the charting of the west African coast stopped abruptly at Cape Nun.

Prince Henry sent out ships with the intention of reaching the kingdoms known to lie beyond the Sahara, and under his orders the chart was gradually extended. Meanwhile he consulted expert opinion and took as one of his advisers a Master James of Majorca, probably the Jew Jafuda Cresques, son of the famous Abraham, chart- and compass-maker to the King of Aragon in 1370–80. In effect, the new method of navigation proposed was what is termed 'running down the latitude', that is to say, the latitude of the port of destination being known, the ship sought that latitude by sailing north or south through the open sea, and then set course due east or due west until within sight of land. This involved something totally new. The medieval sailor had relied on compass and chart, on dead-reckoning and soundings. Now the pilot must know how to make an astronomical observation, he must find the *altura*, as it was termed (actually the latitude), and must know the *altura* of each port of call.

The quadrant. The earliest astronomical instrument used at sea appears to have been the quadrant. As used by astronomers the plate was engraved with a geometrical square as well as the marginal scale of degrees, and had sets of curved lines by which the time of day and the Sun's position in the zodiac could be ascertained by means of a bead on the silk thread which carried the plummet. For the sailor, however, only the angle of elevation of a star was to be measured, by observing it through the pin-holes.

The sailor found the *altura*, or height, of the pole star with which he was already familiar, and there is some evidence that the plate was at first engraved with the names of ports at the correct degree at which the thread should fall. This involved making the observations at one or other of the two positions of the star when it was at the altitude of the celestial pole. Fortunately this was indicated by the position of the Guards, two stars in the Lesser Bear which the sailor was accustomed to observe for time-keeping. He early learnt, too, that 'Guards in the head', that is, towards the northern horizon, meant that three degrees must be added to his observation of the North Star, while 'Guards in the feet', or towards the south horizon, meant that three degrees must be taken away.

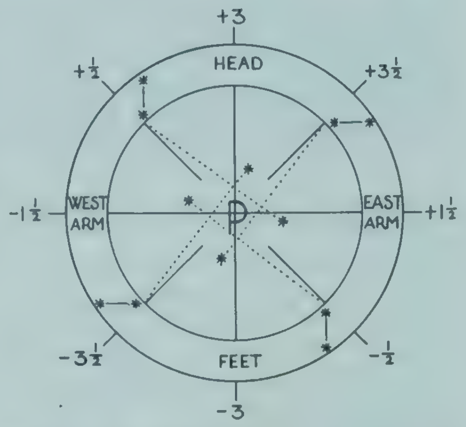

FIGURE 339—*'Regiment of the North Star', showing the position of α-Polaris for four positions of the Guards, and the number of degrees to be added to or subtracted from the observed height of the pole star for eight positions of the Guards.*

Eventually a complete 'regiment of the North Star' was taught, giving the number of degrees to be added or subtracted from the observation for eight positions of the Guards shown on a diagram (figure 339). The maximum correction (that is, angular distance of the star from the celestial pole) was 3° 30′ at that period, and it was more than a century before this figure was reduced in nautical manuals in accordance with the diminution due to the precession of the equinoxes. The concept of 'degrees' is difficult for the non-mathematician to understand, and there is evidence in some extant fragments of early nautical directions that pilots were taught to read a degree as representing a distance of

$17\frac{1}{2}$ leagues (or in some cases $16\frac{2}{3}$ leagues), sailed north or south of their point of departure.

The nocturlabe. Time-keeping by the meridian passage of the stars goes back to ancient Egypt (vol I, p 123). The medieval European night-watcher, whether shepherd or sailor, was accustomed to observe the circling of the Guards of either the Lesser or the Great Bear. A meridian passage takes place approximately an hour earlier every fortnight, and French and Portuguese sailors were taught to relate the midnight position of the Guards throughout the year to an imaginary human figure in the sky. Early in the sixteenth century, however, an instrument came into use that set the twelve months of the year and the twenty-four hours of the day round a circle in such a way that a pointer directed to the date gave also the midnight position of the Guards (figure 363). A second pointer was directed by the observer (who looked to the pole star through a hole in the centre of the instrument) to the actual position of the Guards, when the difference gave him the number of hours before or after midnight. The edge of the circle was toothed so that the hours could be counted round in the darkness, and a refinement was to allow for the eccentricity of the pole star. English nocturlabes or nocturnals of the seventeenth century had two scales, for use with the Guards of the Great Bear or of the Lesser Bear respectively.

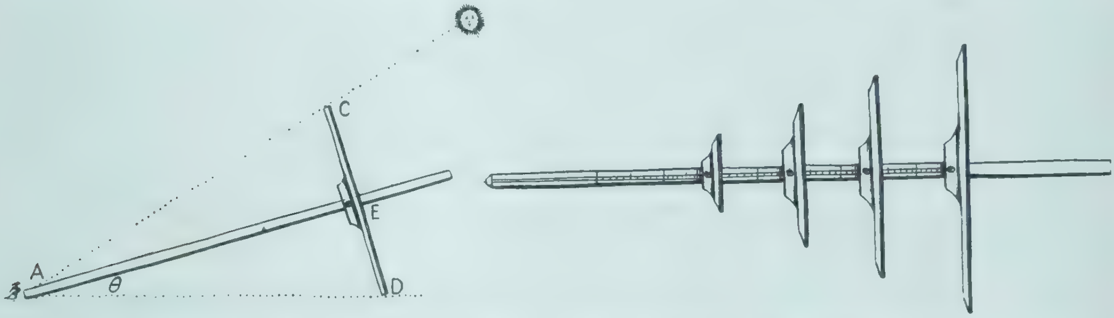

FIGURE 340—*The 'Jacob's staff' or cross-staff.* (Left) *As used in making an astronomical observation;* (right) *fitted with several vertical staves.*

Sea-astrolabe and cross-staff. There is no direct mention of the use even of the sea-quadrant until the middle of the fifteenth century, for seamen were seldom writers. Nor do we know when two further instruments came into use. The sea-astrolabe was merely a heavy graduated circle carrying an alidade or sight-rule, and swinging and swivelling freely from a thumb-ring. It performed the one function needed—taking an altitude. The cross-staff, known to astronomers since its description by the Jewish scholar Levi ben Gerson in the fourteenth century (p 528), was a much cheaper instrument serving the same purpose.

Sailors knew it as the *balestilha*, for they were taught to aim at the star like a cross-bowman (*balestier*) aiming at a mark: they 'shot' the star or the Sun, a mode of expression still employed.

The principle of the instrument is very simple. A transversal can be drawn to and fro along a staff, and half the angle which it subtends is given by $ED/AE = \tan\theta$ (figure 340). The staff can therefore be graduated to show the values of 2θ. The seaman, placing his eye at A, moved the cross-piece until D covered the horizon and C the star. He then read off the *altura*. Before the seventeenth century cross-staffs were made with three, or even four, removable transversals of different lengths, each with a corresponding graduation on the staff. One or other was selected and used according as the heavenly body to be observed stood low or high in the sky.

Regiment of the Sun. At about latitude 9° N sailors used to say that they 'lost the star', and certainly, owing to haze on the horizon and the motion of the ship, they would have found it difficult to observe at its lower transit, while at its upper the Guards would fail them. Yet exploration southward continued. By 1474 the equator was crossed, and in 1482 the castle of El Mina was founded in Guinea. A new technique of navigation was urgent, and Prince (later King) John of Portugal, who was responsible for the African ventures, did as his great-uncle Prince Henry had done before. He brought into consultation astronomers and mathematicians, who devised the rules for finding the latitude by the noonday Sun. This involved calculating a table of the daily solar declination from the Sun's position in the zodiac, which was already tabulated in the *Ephemerides* of Abraham Zacuto (1450–1515?), a Spanish Jew whose disciple José Vizinho had been among those consulted. Regiomontanus had already prepared and printed such a table in 1475 with slightly differing figures. To use the table nine rules were necessary, covering the various positions of ship and Sun on the same or opposite sides of the equator, north or south of each other, or on the equator itself. Vizinho probably made the voyage to Guinea in 1485 to test the rules and establish the latitudes of key points.

Raising a degree. Whether the latitude was found by Sun or star it was necessary to relate change of latitude to distance sailed, and sailors were furnished with a table of the distance that must be covered on each rhumb of the compass in order to raise a degree, or the reverse. The degree was taken by the Portuguese as 17½ leagues of four miles each, that is to say 70 miles, and this figure was probably derived from Eratosthenes's degree of 700 stades, since it is also found in Sacrobosco's *Sphaera*, the text prescribed for pilots' instruction. The earliest surviving printed navigating manual is the Portuguese *Regimento do astrolabio e* *do quadrante*, dated 1509; it is clearly not a first edition, and no doubt also had manuscript predecessors. It contains the rules and tables outlined above, and a list of latitudes from Cape Finisterre to the equator. In a manual of a few years later the declination-table covers the four-year cycle, and the latitudes extend to the Indies.

Christopher Columbus (1446?–1506) appears to have known and used an early Portuguese manual, but after the discovery of America the development of navigation was also fostered by Spain, and pilots were trained at the *Casa de Contratación* or chamber of commerce. Spanish manuals were published in 1545, 1550, and later, and one of them, by Martin Cortes (1532–89), provides the necessary rule to be used with that for raising a degree, namely how much easting or westing is made according to the rhumb on which the ship sailed. This was given in terms of the 'great' or equatorial degree of 17½ leagues, and a table was also furnished of the proportion the degree of longitude in each latitude bore to the great degree. Hence a pilot or chart-maker had the means to interpret the ship's run in terms of latitude and longitude. In fact, however, estimates were often grossly at fault.

The plain chart. Mathematicians commonly decried the 'plain chart' as a major cause of disaster at sea. Based as it was on the pattern of rhumb-lines laid down for the medieval chart of the Mediterranean Sea, it showed all north–south lines as parallel, and hence increasingly falsified east–west distances with distance from the equator. In fact, however, as Cortes states, the scale was usually made correct along some middle latitude of the chart, and hence the distortion was lessened, nor were any lines of longitude indicated. Nevertheless, if two points had been placed the correct distance apart on the chart then their bearings were falsified, and vice versa; yet pilots were accustomed to lay off bearings and distances with confidence from such charts.

In 1537 the Portuguese mathematician Pedro Nuñez (1492–1577) analysed the causes of error at some length and pointed out the true course of a rhumb-line (line of constant bearing), which is a spiral on the surface of the globe. In fact, however, there was no substitute for the plain chart until the chart on Mercator's projection was invented and (much later) accepted by sailors. Meanwhile, some captains took globes to sea, but the size and clumsiness of these devices, not to say their inaccuracy, rendered them of little use. A further source of error in the plain chart arose from the variation of the magnetic needle, causing the bearing which the pilot entered in his journal to be incorrect.

Magnetic variation. The Nuremberg compass-dial makers noticed that the magnetic needle did not lie precisely in the meridian, and scored the dial to show where it should be when the instrument was correctly oriented. Compass-makers, too, noticed the same phenomenon, and fastened the magnetized wire a little askew under the card so as to correct the fault. The correction differed according to the port where the compass was made, and in some cases was not attempted at all; the instrument was then called a meridian compass. Portuguese sailors must have noticed that their corrected needles swung westward as they approached the Azores, and eastward again as they returned to Lisbon. Columbus remarked on the fact that his different needles did not agree, and that there was a marked north-westing when he passed the Azores into the undiscovered hemisphere. In the old world north-easting was the general rule.

Pilots of standing, and their mathematical advisers, urged the regular instrumental observation of the variation. The principle of the methods proposed was to compare the true meridian as found by equal-altitude observations of the Sun with the magnetic meridian as found by simultaneous readings of the Sun's amplitude or azimuth. The earliest instrument was a graduated circular plate carrying a central style and an inset magnetic needle by which the zero reading was set due north. The west and east bearings of the shadow of the style were read when equal-altitude forenoon and afternoon observations of the Sun were taken with the astrolabe. Half the difference between the needle and Sun bearings is the magnetic variation. Alternatively the Sun can be observed at the moments of rising and setting. A later form of instrument was a large magnetic compass, carrying a scale of degrees as well as the ordinary scale of rhumbs, and fitted with a sight-rule or alidade and a thread for casting a shadow. The making of a pair of observations presented difficulties on a moving ship, and most pilots appear to have been satisfied with a rough check on the compass when they took the noon Sun. Mathematicians were aware, however, that the amplitude of the Sun when it rises and sets can be calculated if the solar declination and latitude are known, and all that is then necessary is to compare the true and the magnetic amplitudes at either sunrise or sunset. Amplitude-tables were first used towards the close of the sixteenth century.

The log. The sixteenth-century master or pilot kept his reckoning on a traverse-board hung in the steerage. It was a circular board marked out with the 32 rhumbs, along each of which were equally spaced peg-holes. By means of pegs the number of hours and half-hours sailed along each rhumb in the course of the day was marked off, and from these data, coupled with his estimate of the way of the ship under the prevailing wind, each officer or would-be officer worked out the ship's position when the noon Sun was taken, using the departure-tables in the navigating manual to resolve the course. In England, however, some time before 1573 an instrument was devised to determine the ship's way more precisely. This was the log-and-line, quickly imitated by French and Dutch sailors, although not by the Spaniards and Portuguese. A wooden board, weighted at one edge with lead to make it ride upright, was attached to a length of line on a reel, knotted at equal intervals. The log was thrown overboard from the stern of the ship, and after it was clear of the dead water under the ship a half-minute sand-glass was turned and the linesman counted the knots that ran through his hands until his mate cried to him to stop, as the sand ran out. The knots were so spaced (at about 7 fathoms) that the passage of each one during the half-minute represented a rate of one mile an hour. Hence if three knots passed the ship was 'making three knots' or three miles an hour. When, during the seventeenth century, it was established (in the first instance by Richard Norwood, *c* 1590–1675) that the measure of the degree was over 69 miles and not the 60 miles accepted by English sailors, the situation was met by re-knotting the log-line at a wider interval using the correct proportion. The sailor's method of reckoning remained unchanged, and there were still 60 sea-miles to a degree, but each of these was equal to a minute of arc of the great circle, and corresponded in length to the best measure made of the latter. Complaints were to be heard, both in England and France, that even in the eighteenth century the old seven-fathom log-line was still in use, but this was often adjusted by the use of a sand-glass running for only 27 seconds instead of the full 30 seconds.

The Mercator chart. Gerard Mercator (1512–94) as a young man was the mathematical pupil and assistant of Gemma (Reiner) Frisius (1508–55), and an able instrument-maker and globe-maker. He became a professional cartographer and, familiar as he was with the strictures on the plain chart, invented a new projection for marine charts in 1569. The essential feature of this projection, upon which he published a large map of the world, was that, unlike the plain chart, it gave true bearings or rhumb-lines between any two points. The ship's course could be found by laying a ruler across the map. On the plain chart north–south distances were kept true, but east–west distances were increasingly exaggerated with distance from the equator, since the convergence of the meridians was ignored. If north–south distances were exaggerated *pari passu* with east–west, then there would be no distortion of bearings. The required exaggeration is in the ratio of the secant of the latitude, but Mercator did not explain this; he merely gave a graphical device showing how his map could be used to solve the nautical triangle, in which the elements are bearing and distance, *d. lat.* and *d. long.* Not until towards the close of the century was Mercator's principle brought in a practical form to the notice of chart-makers and sailors.

Two English mathematicians, Thomas Harriot (1560–1621), working privately for Sir Walter Ralegh, and Edward Wright (1558–1615), a professional 'mathematical practitioner', both making use of the trigonometrical tables now available, drew up the tables of meridional parts, as they were termed, by which the lines of latitude on a Mercator chart should be spaced. This table was built up by the continuous addition of secants of the latitude at minute intervals. Wright explained its use in his text-book 'Certain Errors in Navigation' (1599), which included a map of the north Atlantic on the new projection. Instructors in navigation immediately began to teach sailing by the Wright–Mercator chart, and in 1614 one of them, Ralph Handson, published the six cases of the nautical triangle and their trigonometrical solutions. He pointed out, as Stoeffler had done for cosmographers a century earlier, that for *d. long.* the scale of the middle parallel of the triangle must be used.

Longitude. The problem of finding the longitude at sea remained intractable, although many theoretical methods were known and even attempted. Precise timing of celestial events, such as a lunar eclipse or the occultation of a star by the dark limb of the Moon, awaited improvements in horology, as did the carrying of an exact timepiece recording the time at the point of departure. The measurement of lunar distances, and indeed all measurements involving the Moon, were vitiated by the imperfection of lunar tables; nor were the catalogues of the fixed stars precise. The results obtained by John Flamsteed (1646–1719) at the Royal Observatory were not published until early in the eighteenth century. It has also to be remembered that nautical instruments and tables remained generally coarse, and that while during the seventeenth century some manuals introduced the idea of corrections for atmospheric refraction, for dip of the horizon, and for parallax, the correction-tables were imperfect and the seamen indifferent.

Hopes for the longitude were, however, twice raised during the century. Galileo's telescope had long ago revealed Jupiter's satellites, which are very frequently eclipsed. Both in England and France a beginning was made during the second half of the seventeenth century in tabulating the occurrence of these eclipses, but the 6-ft telescope required for their satisfactory observation could not be successfully used at sea, while the mirror of the short reflecting telescope[1] rapidly tarnished when damp. The second invention that seemed to offer possibilities of success was Huygens's pendulum clock (1659), that is to say, a new, reliable timepiece, but after repeated trials it had to be admitted that such a clock was not trustworthy at sea (p 557). Perfected lunar tables were believed to be the answer.

[1] First suggested by James Gregory in 1663, and successfully made by Isaac Newton in 1668.

The back-staff. During the seventeenth century the old nautical instruments—astrolabe, quadrant, and cross-staff—were very generally superseded by John Davis's back-staff, first described in 1595, and known to foreign sailors as the English quadrant (figure 341). The advantage of the instrument was not only that the observer turned his back to the Sun: he no longer had to 'blink' simultaneously at horizon and heavenly body. There were two arcs carrying movable vanes, the upper one being adjusted to the approximate height of the Sun so that its shadow fell on the forward sighting-slit, while with the lower arc the user then sighted precisely on to the horizon. Later patterns had a lens affixed to the sun-vane so that a spot of light cast through it was substituted for the shadow on the forward slit.

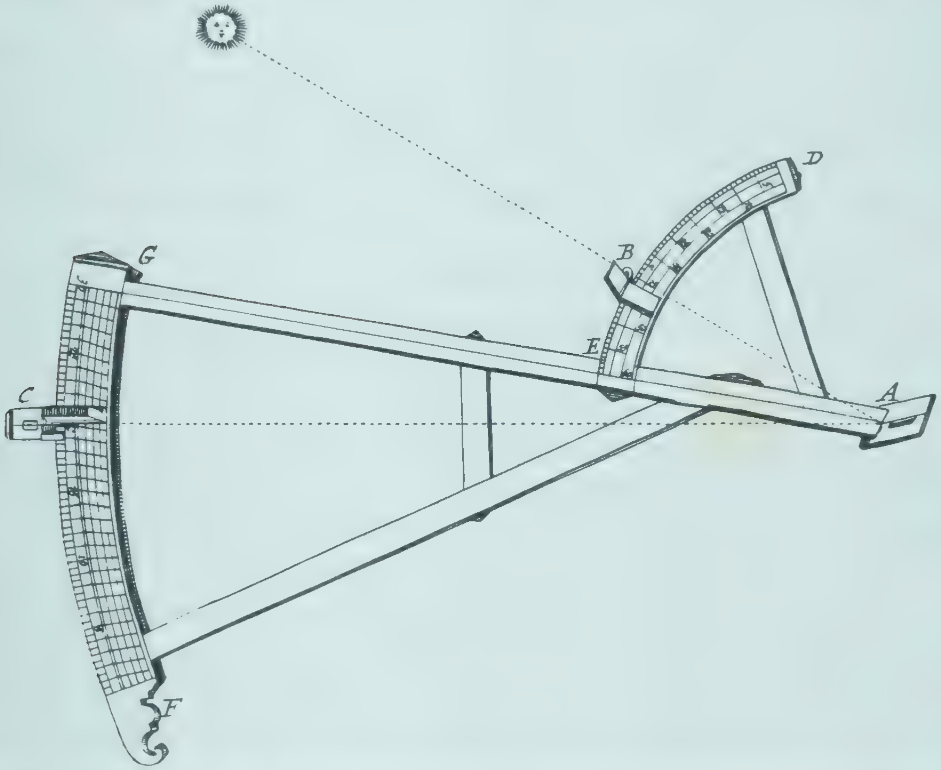

FIGURE 341—*The back-staff. The observer has the Sun behind his shoulder and looks at the horizon through the sight* (C) *and the slit in the vane* (A). *Having set the shadow-vane* (B) *by estimation, the sight* (C) *is adjusted until the shadow of the upper edge of* (B) *falls on the upper edge of the slit in* (A), *with the horizon seen through the slit. Adding the readings of the two scales gives the zenith-distance* (*complement of the latitude*). *The larger arc* (FG) *is divided diagonally so that fractions of a degree may be read more accurately.*

Nautical tables. In England a 'Seaman's Kalendar', containing the *Ephemerides* of the Sun and Moon and tables of the most notable fixed stars, was first published in 1600, and was edited by a succession of private teachers of navigation. A rival 'Mariner's New Kalendar' appeared in 1676, and continued to be published for over a century. In France the semi-official *Connoissance des Temps* began to appear annually under royal licence in 1678–9, edited by a member of the Académie des Sciences, and has continued publication ever since. Although not specifically a nautical almanac it included the tables necessary for sailors. A seamen's manual was expected to contain tables of meridional parts, distance and departure tables (for resolving the course) for every quarter rhumb ($2\frac{7}{8}°$) and for every degree, as well as logarithm tables for the natural numbers and trigonometrical functions, and tide-tables.

IV. THE EIGHTEENTH CENTURY

No new principles were introduced into survey and cartography during the eighteenth century, but plane-table, theodolite, and level were used with increasing refinement. This is exemplified in the procedures adopted in France for determining the shape of the Earth by re-measuring the arc of the meridian. The spherical shape had been called in question both by observations made with the pendulum and by Sir Isaac Newton's assumption on theoretical grounds that the globe was an oblate spheroid. This conflicted with the measurements made by the second Cassini (p 544) when he extended the meridian measured by Picard to the south of France. These pointed to an ovoid shape, with the polar diameter exceeding the equatorial. Louis XV ordered expeditions to be organized to make fresh measurements near the equator and near the Arctic circle, the latter being described in detail by a member of the party, the philosopher Maupertuis (1698–1759).

The principle to be employed was that adopted by the Arabs in the tenth century, namely to observe the meridian altitude of a star, to travel north or south until its altitude had changed by one degree, and to measure the distance travelled. The French party went to Finland, then Swedish territory, and set up two observatories (at Tornea and Kittis) approximately in the same meridian and about one degree of latitude apart. In each, the direction of the meridian was laid down precisely by repeated observations of the meridian passage of the Sun and of selected bright stars.

The clock used for timing observations was one made by the famous George Graham (1673–1751) of London, regulated daily by observation of matching forenoon and afternoon altitudes of the Sun, and used in combination with a seconds pendulum. At the moment of their meridian passages, the altitudes of two stars close to the zenith were to be observed, since this would eliminate the errors due to atmospheric refraction. The instrument used (called a 'sector'), also made by Graham, consisted of a 9-ft telescope mounted so as to hang vertically. It was so delicately poised that it could be directed on the star by means of a micrometer screw, the revolutions of which were counted from its initial position. The silver cross-wires in the focus of the telescope had been fixed on springs so that they were held at constant tension in spite of the extreme temperature changes to be expected, for the observations were to take over a year (1736–7). The limb of the instrument had been graduated by Graham personally, and the index-error determined, but the scientists took the precaution of calibrating the divisions by passing the scale under a pair of diverging taut wires over each of which a microscope was fixed. The observed altitudes were corrected for the minute change in stellar positions due to the precession of the equinoxes between the dates of observation at the respective stations, and for the phenomenon of aberration recently discovered by the English astronomer Bradley.

The distance between the two points of observation was measured with equal care. A number of visible hill-top beacons were established, whose positions were to be observed from either extremity of the base-line. This was about 8 miles long, and was pegged out between two signal-posts on the frozen and level surface of the river Tornea. The measuring was done by two independent parties carrying 30-ft measuring-poles of fir-wood. These had been tested under different temperature conditions, when it was found that they expanded or contracted almost imperceptibly, by 'the thickness of a leaf of the finest paper, more or less'. The two sets of measurements differed by a mere 4 in, and the mean values were taken. After the triangulation was completed and the distance between the observatories calculated, the savants were astonished to find that the degree near the Arctic circle was nearly a mile longer than Cassini's theory had predicted, and definitely longer than Picard's degree measured just north of Paris. The Earth was in fact flattened at the poles, a result amply confirmed by the expedition sent to Peru to carry out a similar measurement, whose return was delayed until 1745. The length of the degree at each latitude was thus established with sufficient accuracy for navigational and cartographic purposes.

A map of France, based entirely on triangulation, was begun in 1744 by Cassini de Thury, and took almost forty years to complete. In 1784 the English military engineer William Roy (1726–90), who as a young captain had mapped the Highlands of Scotland after the rebellion of '45, undertook a triangulation in southern England which was to link across the Channel with the French geodetic survey. The necessary base was measured on Hounslow Heath, and a few years later (1791) the Ordnance Survey was officially instituted. During the century much detailed topographical survey was carried out on the continent in various theatres of war by other military engineers, who developed the convention for indicating slopes on maps by precise hachuring. Pen or pencil strokes were drawn downhill, being made thicker on steep slopes, finer on gentle slopes. Towards the end of the century the length, width, and spacing of the strokes were made systematic, so that actual gradients could be indicated. The increasing observation and recording of heights above sea-level also enabled the first contoured map, one of France, to be drawn in 1791. Improvements in instrument-making, such as John Dollond's invention of the achromatic lens in 1758 and Jesse Ramsden's of a scale-cutting machine in 1775, also advanced the accuracy of cartography together with that of other observational sciences.

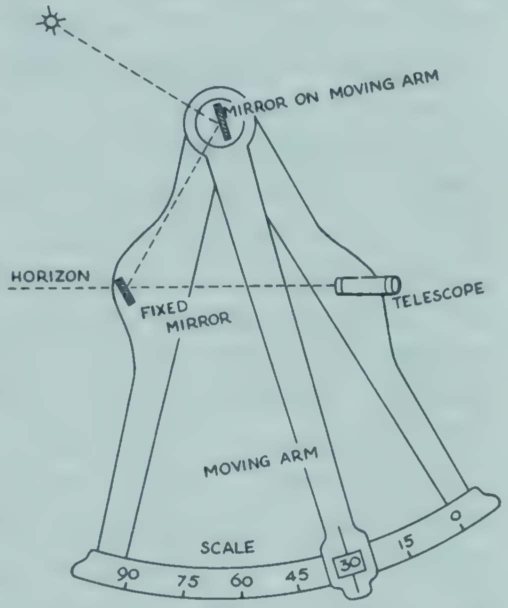

FIGURE 342—*The principle of Hadley's octant. When the included angle of the instrument is* D°, *the angle of both the fixed mirror and the movable mirror (in the zero position) to the axis of the instrument is* $(45-D/4)^\circ$. *When the index is moved* d° *from zero, the angle of incident light must be raised* $2d^\circ$ *to enter the telescope or sight.*

Improvements in the seaman's equipment were foreshadowed by the publication in 1686 of the first wind-chart (trades and monsoons) compiled by Edmond Halley (1656–1742) and by the same author's chart of the variation of the magnetic compass. Including his own recent observations at sea, the figures were expressed by Halley as interpolated isogonic lines[1] drawn over the most frequented oceans at intervals of one degree. This was the earliest isometric map. Users were warned of the secular change in the variation, and about the middle of the eighteenth century the chart was revised by Mountaine and Dodson to include the very large number of observations by then available. These were the more reliable owing to the introduction of improved mariners' and azimuth compasses made under the direction of Dr Gowin Knight (1713–72), who used magnetized steel bars instead of lodestones for 'touching' the needle.

Meanwhile a great advance followed the introduction of John Hadley's quadrant, the principle of which had been anticipated by Robert Hooke and Isaac Newton, but since forgotten. If a mirror is fixed opposite to the sighting-tube or telescope of a quadrant, and a second mirror, parallel to the first in the zero position, is placed on the arm of the quadrant which moves across the limb (that is, the scale) at the pivotal point, then an object such as a star can be reflected from one mirror to the other and down the tube so that it appears to coincide with an object seen directly. The angle between the two objects is then twice the angle between the two mirrors (figure 342). The angle of 90° (quadrant of a circle) is thus read off on a scale of 45° (octant) and to facilitate reading the value of each degree-division on the scale is doubled. Hadley devised his quadrant for bringing a star down to the horizon. Only one-half of the fixed mirror was silvered, so that when the movable arm stood at zero the reflected and the directly observed horizon-lines coincided.

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[1] Lines of equal variation.

The supreme advantage of the instrument is that, once a star is brought by reflection to the horizon (or, say, to the rim of the directly observed moon), it remains there, no matter what the motion of the ship. The principal reason for the crudity of readings at sea being thus removed, it became worth while to fit the instrument with a bubble-level (for it should be held vertically) and a vernier giving fine readings on the limb. Introduced by Hadley before the Royal Society in 1731, the octant was immediately tested and approved by the British Admiralty, and by 1733 was being copied and used in France. In 1738 the instrument-maker George Adams (d 1773) was offering a cheaper form of the instrument than Hadley's, and in his booklet also describes the invention of the artificial horizon —a trough of mercury which affords a horizontal reflecting surface. The star as reflected from the movable mirror is brought into coincidence with the image of the same star reflected from this surface, seen directly. The angle thus found is equal to twice the elevation of the star above the horizon. The advantage of the new device is that the frequent obscurity of the visible horizon is overcome, as well as the uncertainties of atmospheric refraction, while the correction for the dip of the horizon below the observer's eye becomes unnecessary. By 1757 the limit of the octant was extended to cover rather more than 120°, so that its included angle was now rather over 60°, and it thus became a sextant. Besides its daily use for 'taking the Sun' at noon (when a dark glass is turned between the mirrors), and for measuring lunar distances (the angle between a star and the Moon's rim), the sextant can be used for taking horizontal angles. Thus the standard of hydrographical charting was improved, as it was also by the introduction of the plane-table and of the method of triangulation where it was possible for the seaman to work ashore.

Astronomical observations by scientists on shore, based on eclipses, on lunar distances, or on the appearance and disappearance of Jupiter's satellites, taken in combination with the improved time-keeping now possible at a stationary point of observation (ch 24), led to a lengthening list of accurate longitudes and consequent improvement of maps and charts. At sea, however, on a travelling ship, no such accuracy was possible, while the determination of longitude even to a single degree does not provide safety. An Act of Parliament of 1714 offered a reward of £20 000 for a device for determining longitude at sea, the test being that the method was to be accurate to within half a degree during and after a voyage to the West Indies and back. It was generally assumed that the solution lay in a precise time-keeper, that is, a chronometer correct to within two minutes at the end of such a voyage. In France a generous prize was offered with a similar object. Improvements in horology, associated with the names of Thomas Tompion (1639–1713) and George Graham in the one country, and of Sully and Julian Leroy in the other, had still not dealt with the difficulty arising from the expansion and contraction of metal parts with temperature changes (ch 24).

The younger Leroy and John Harrison (p 672) gave themselves to this problem for many years, and the latter was successful with his fourth chronometer (the first was made in 1731) in 1763. The British Admiralty imposed rigid tests on the English time-piece both at sea and at the Royal Observatory, and Harrison did not receive the full award until shortly before his death. A facsimile of his 'No. 4' (a watch-type) made by a clockmaker, Larcum Kendall, was carried by Captain Cook (1728–79) on his second voyage, when it proved its worth. Since, however, the cost of such an instrument ran into hundreds of pounds, there was an interval before it could be cheapened for general use. The Admiralty did not order a general issue to the Royal Navy until 1825. Meanwhile the method of lunar distances had been greatly improved, not only by the refinement of the sextant but by the precise lunar tables published by the Astronomer Royal, Nevil Maskelyne (1732–1811), who first issued an annual 'Nautical Almanac' in 1767; it was later continued by the Admiralty. In France annual astronomical tables are published by the Bureau des Longitudes, continuing those first edited by Picard under the title of *Connoissance des Temps* in 1679.

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21

THE CALENDAR

SIR HAROLD SPENCER JONES

A CALENDAR is a method of combining days into periods, such as weeks, months, and years, for the convenience of civil life, the guidance of day-by-day activities, and the fixing of religious feasts and observances.

Attempts to construct a satisfactory calendar go back to the dawn of civilization. It was primarily with this end in view that the observation and recording of the positions of the heavenly bodies, of the phases of the Moon, of eclipses, and of other celestial phenomena were first undertaken.

The three astronomical periods of most importance in everyday life are (i) the period of the rotation of the Earth on its axis, the day, giving the alternation of day-time and night-time associated with the rising and setting of the Sun; (ii) the period of the revolution of the Moon around the Earth, with the sequence of its phases, giving the month; (iii) the period of the revolution of the Earth around the Sun, with the sequence of the seasons, giving the year.

The sidereal revolution of the Moon is the period occupied by the Moon in passing from a given star back again to the same star. Its average length is 27·321661 days. The synodic revolution, generally known as the lunation or lunar month, is the period from new Moon to new Moon, or from full Moon to full Moon. Its average length is 29·530598 days. The actual length is not constant, because the orbits of the Moon round the Earth and of the Earth round the Sun are slightly elliptical and because of the perturbations of these orbits; the extreme range in the true length of the lunar month is about thirteen hours.

The sidereal year is the period of a revolution of the Earth round the Sun, relative to the fixed stars. It is the year determined, for example, by observation of the 'heliacal risings' of stars, that is, by the first appearance of conspicuous bright stars, such as Sirius, in the morning twilight near the eastern horizon. Its length is 365·256360 days.

The natural unit marked out for the use of man is not, however, the sidereal year. It is the period of revolution of the Earth relative to the First Point of Aries (the apparent point in the heavens where the path of the Sun—the ecliptic—crosses the equator from south to north); this period determines the commencement of the seasons and all associated phenomena. It is called the tropical year and its length is 365·242199 days: its length was determined by the ancients by the use of the gnomon. The sidereal year is about 20 minutes longer than the tropical year, this difference being due to the retrograde motion of the First Point of Aries resulting from the precession of the Earth's axis. The difference in the lengths of these two years was determined with fair accuracy about 130 B.C. by the Greek astronomer Hipparchus.

The complexity of the problem of devising a satisfactory calendar is due primarily to the incommensurability of the three natural periods of time: the day, the month, and the year. Thus the tropical year contains 12·368267 lunations. Further, the first attempts at the formation of a calendar were made long before the lengths either of the lunation or of the tropical year were known with any accuracy. The beginning of the lunar month was customarily fixed either by the first appearance of the crescent of the new Moon in the evening sky after sunset, or by the first invisibility of the crescent of the old Moon in the morning sky before sunrise. The first or last visibility of the crescent Moon depends, under clear conditions, on several variable factors; the principal of these are the angles which the ecliptic and the plane of the Moon's orbit make with the horizon; the distance of the Moon north or south of the ecliptic; and the distance of the Moon from the Earth. In the latitude of Babylon the time after new Moon at which the crescent can first be seen may be as short as 16 hours or as long as 42 hours; there is a corresponding range in the times before new Moon at which the crescent can last be seen. Superposed on these variable conditions of visibility is the variable length of the lunation itself.

For the work of primitive man the cycle of the seasons was by far the most important period. Most of his activities were regulated by this cycle, whether, as in northern latitudes, it involved a cold winter, in which the earth was dormant, and a warm summer, in which crops could be raised; or whether, as in lower latitudes, it involved an alternation of dry and wet seasons; or whether, as in Egypt, it was bound up with the annual flooding of the cultivable land. Hunters and fishermen might be dependent upon the seasonal migration of animals and fish. As phenomena dependent on meteorological causes, such as the beginning of the rainy season or the flooding of a river, are too irregular in their recurrence to serve as reliable guides to the proper times for preparing the ground, for sowing, and for harvesting, some more certain guides were needed. The variability of the length of the lunation, as determined from the visibility of the crescent Moon, and the fact that the times of new or full Moon did not recur at the same periods each year, combined to make the Moon an uncertain guide.

From very early times it was known that different constellations were visible at different seasons of the year. As the Sun has an apparent eastward motion relative to the stars of about 1° a day, any given star crosses the meridian and is due south about four minutes earlier each day. Amongst the Babylonians and Egyptians, as also amongst the Greeks and Romans, it was customary to observe the heliacal risings of bright stars to indicate the passage of the Sun amongst the stars. Thus in Egypt the periodic flooding of the Nile usually began soon after the summer solstice and its coming was heralded by the heliacal rising of Sothis or Sirius, in the month of June.

The gnomon, a stick stuck vertically into the ground, served with some peoples to mark the succession of the seasons. Its use is bound up with the northward and southward motions of the Sun relative to the stars in the course of the year. At the summer solstice the Sun rises farthest north of east and sets farthest north of west; at the winter solstice, it rises farthest south of east and sets farthest south of west; at the equinoxes it rises due east and sets due west, directions which are midway between the directions of rising and setting at the summer and winter solstices. These positions could be marked out by stones and, when once marked, were a sure guide to the time of year.

The length of the tropical year exceeds 12 lunations by about 11 days. Consequently when the month was the lunation, whose beginning was obtained by observation of the lunar crescent, it became necessary every two or three years to intercalate a thirteenth month; these intercalations originally took place at irregular intervals when it appeared that the months were deviating too far from their proper seasons. Gradually, with the emergence of a priestly caste, one of whose duties was to ensure that the religious festivals were observed at the proper seasons of the year, the regulation of the calendar became one of their principal functions. Records were kept, regularities were noted, and cycles were determined which facilitated prediction and served as a basis for providing a calendar system. But there was a great variety in the nature and complexity of the various calendar systems that were developed amongst different peoples and at different times. It is the purpose of this chapter to consider some of these early calendars.

I. THE EGYPTIAN CALENDAR

The most important event in the year in the agricultural life of Egypt is the annual flooding of the Nile, as it is upon this flood that the fertility of the narrow cultivated strip of land along each bank depends. The year in Egypt was in early times divided into three seasons—flood time, seed time, harvest time—each containing four months. Though the months were given names derived from the important feasts celebrated in them, they were always designated in hieroglyphics by their position in the season to which they belonged. The first month of the first season, which began the year, was called Thoth, which is equivalent to Seth or Sothis, the name of the brightest star, Sirius, whose heliacal rising in June foreshadowed the flooding of the Nile. This suggests that the Egyptians, when a rigid time-reckoning was introduced, began the year with the heliacal rising of Sirius.

The day in Egypt began at dawn and was reckoned from one dawn to the next. It was natural, therefore, that the month should begin on the morning of the day when the crescent of the old Moon was no longer visible in the eastern sky before sunrise. The original Egyptian calendar was purely lunar. Some time in the fourth or fifth millennium B.C., when the heliacal rising of Sirius and the start of the Nile inundation were near together in time, Sirius, or Sothis, came to be regarded as the harbinger of the inundation; and its heliacal rising was adopted as the starting-point for a purely lunar calendar, containing three seasons each of four months, the commencement of each month being determined by observation of the invisibility of the crescent of the old Moon. The beginning of the year was the first day of invisibility of the crescent Moon after the heliacal rising of Sirius. It must have been recognized quite soon after the introduction of this calendar that, though the intervals between successive inundations of the Nile were very variable, the intervals between successive heliacal risings of Sothis were practically constant and that they exceeded the length of 12 months by some 11 days. It thus became necessary at intervals of three—or occasionally of two—years to intercalate a thirteenth month. This intercalation appears, from the discussion by Parker of the evidence from various inscriptions and papyri, to have been made whenever the first month began within 11 days of the heliacal rising of Sothis; it was thereby ensured that the feast called 'Opener of the Year', which marked the time of the heliacal rising, was always celebrated in the twelfth month [1]. The intercalary month was dedicated to Thoth and a feast of this god was celebrated in it.

In course of time, as a well organized economic life developed in Egypt, the inconveniences became apparent of a calendar in which the year sometimes had twelve months and sometimes thirteen, the beginning of each of which had to be fixed by observation. The idea of a fixed civil year, based upon an averaged lunar year, was conceived. From records of the actual lengths of the lunar years in previous decades, it could readily be found that the average length was very close to 365 days; records kept for a few years of the heliacal rising of Sirius would also show that the average interval between successive heliacal risings was 365 days. So the introduction of a fixed civil calendar followed: in this calendar the length of the year was taken to be 365 days, and the year was divided into three seasons, each containing 4 months, each month having 30 days. The extra 5 days were intercalary and were placed before the first month of the year, in the same way that the intercalary month of the lunar calendar, when it was needed, always headed the lunar year. The circumstances of the introduction of this civil calendar are uncertain, but Parker has shown that there is a strong probability that it came into use early in the third millennium B.C.

The two calendars were used concurrently. The fixed civil calendar served for the regulation of secular matters, while the lunar calendar continued to be used for religious purposes, such as the determination of feasts. For some time it would not have been detected that the adopted length of the civil year was too short by about 6 hours, causing the fixed calendar to move forward through the seasons by one day every 4 years, for the interval between successive heliacal risings of Sirius was 365 days to a good approximation, while the variability of the lunar calendar was sufficiently large for general agreement between the civil and lunar years to persist for many decades.

But eventually, after perhaps two centuries, it could no longer have escaped notice that the first month of the civil year ended before the first month of the lunar year had begun. The fixed civil calendar and the lunar calendar based on observation had gradually drifted out of phase with one another. The civil calendar had by that time become so well established and had proved so convenient that there was no question of forcing it back into agreement with the lunar calendar.

The difficulty was solved by an ingenious device—the creation of a special lunar year, whose sole purpose was to maintain the parallelism between the lunar and civil calendars that had existed when the civil calendar was introduced. The beginning of each lunar month was still obtained by observation as before, but, by suitable intercalation of a thirteenth month, the new lunar year maintained its general agreement with the fixed civil year. The original lunar calendar, tied, as we have seen, to the heliacal rising of Sothis, continued in use as before, while the later lunar calendar was free to progress through the seasons along with the civil calendar. It is not known precisely when the second lunar calendar was introduced, but Parker considers that it was likely to have been around 2500 B.C. From the time of its introduction, three calendar years were in use in Egypt, all of which continued in use to the very end of pagan times.

At a much later date this second lunar calendar became stereotyped into a schematic form, the lengths of whose months were fixed by definite rules instead of by observation, but in such a way that the beginning of each month fell very close to the true new moon. Most of the details of this schematic calendar are given in the Papyrus Carlsberg 9, which was written in or after A.D. 144 and which is stated by Parker to be the only truly mathematical astronomical Egyptian text yet published (vol I, p 797 and plate 36). There is evidence to prove that this calendar was in use long before A.D. 144 and Parker, from the discussion of this evidence, concludes that it was introduced somewhere about the year 357 B.C.

The complete details of this later lunar calendar have been reconstructed by Parker with very little uncertainty. The calendar was in the form of a 25-year cycle in which each month had a length of either 29 or 30 days, so arranged that there were never more than two consecutive months of the same length. A thirteenth month was intercalated in the 1st, 3rd, 6th, 9th, 12th, 14th, 17th, 20th, and 23rd year of each cycle, these years being known as 'great' years. The rule determining the intercalation was that a month was intercalary whenever the first day of the lunar month Thoth would fall before the first day of the civil month Thoth. In the complete cycle of 25 years there were accordingly 309 months; 145 of the months had a length of 29 days and the other 164 had a length of 30 days. The duration of the cycle was consequently 9125 days, which gave for the average length of a year through the cycle exactly 365 days, in agreement with the length of the Egyptian civil year. The precise length of 309 lunar months is 9124·9517 days, which differs from the length of the 25-year cyclic lunar calendar by not much more than one hour. Thus it follows that the beginning of each month could never deviate by much more than a day from the true new Moon, an amount which is within the uncertainty of the observation of the invisibility of the old lunar crescent.

The Egyptians were the first people to determine the length of the year as 365¼ days, although their civil year was given a fixed length of 365 days. Their determination of the length of the year was probably based on observation that the heliacal rising of Sirius occurred on the average a day later every four civil years, causing the civil calendar to progress slowly through the seasons. Taking the length of the natural year as 365¼ days, they formed a cycle of 1461 calendar years which were equated to 1460 natural years, this cycle being known as the Sothic cycle. The length of the sidereal year is 365·2564 days and is thus not strictly 365¼ days; but Schoch has shown that the heliacal rising of Sirius, a star with a very large proper-motion, recurred after a mean interval of 365·2507 days, giving 1456 years as the precise length of the Sothic cycle, after which the heliacal rising would occur on the same date in the calendar year [2]. Censorinus in the third century A.D. called a year in which Sirius, the dog-star, was first seen in the morning twilight on the first day of the first month Thoth, an *annus canicularis*. Ideler concluded that this occurred in the years 2782 B.C. and 1322 B.C., and supposed that the introduction of the civil year fixed at 365 days occurred in the latter year [3]. Neugebauer and Parker both consider the most probable date to have been *c* 2800 B.C.

But long after the length of the year was known to be $365\frac{1}{4}$ days, the movable year of 365 days continued to be used, until, in fact, the introduction of the Alexandrian calendar, probably in the year 26 B.C. In the ninth year of Ptolemy Euergetes, 239 B.C., the great assembly of priests at Canopus passed a decree, according to which an additional day was to be inserted every fourth year in order to arrest the forward movement of the civil year. This decree was of no effect at that time and the civil year continued to have a length of 365 days. The first undisputed fixed year in Egypt came with the introduction of the Alexandrian calendar, in which this change—the insertion of an additional day every fourth year—was made; the first day of Thoth in this calendar coincides with 29 August (or in leap year 30 August) in the Julian calendar. But the old calendar still remained in use along with the reformed calendar until well into the third century A.D.

The Egyptian civil calendar is of importance in chronology because, until the Julian reform of the Roman calendar in 46 B.C., it was the only calendar in which the length of each month and of each year was fixed by an invariable rule and not left to be varied at the whim of officials. For astronomical purposes it had the great convenience that the exact number of days between any two observations, whose dates in the Egyptian calendar were known, could be determined with ease and certainty. Thus we find Hipparchus, who observed at Rhodes, reducing Chaldean observations to the Egyptian calendar.

The Egyptians did not use a definite era from which to date events, but referred always to the year of the reign of the king in which an event happened. Both Hipparchus and Ptolemy accordingly used for convenience an era dating from the beginning of the reign of Nabonassar, founder of the kingdom of the Babylonians, known as the era of Nabonassar. This era begins with midday on the 1st day of Thoth of the first year of the reign of Nabonassar, corresponding to 26 February in the year 3967 of the Julian period, or 747 B.C. At the beginning of the era 1 448 658 days had elapsed in the Julian period. This era was of great convenience for scientific purposes, but was never used in ordinary everyday life. The year used for dating events in this era was the Egyptian year of 365 days. By means of the famous Canon of Kings, prepared by Ptolemy, dates in Babylonian and Egyptian history, expressed in terms of the year of the reign of the then king, can be conveniently converted into dates in the era of Nabonassar.

The Egyptians began the day with sunrise; they divided the interval from sunrise to sunset into 12 equal hours, and the interval from sunset to sunrise also into 12 equal hours. The daytime hours were necessarily of different length from the night hours, except at the equinoxes, and both the day and night hours varied in length according to the seasons of the year. The hours so provided were known as temporal hours.

The seven-day week is not an interval of time that is marked out by any celestial motions. It was introduced into Europe from the Assyrians, and then from the Jews it was taken over by the Christians. The Egyptians divided the 30-day month of their civil calendar into three decans, or 10-day periods. There were 36 decans in the year, to each of which corresponded a divinity. There are two series of divinities connected with the year in Egypt; one consists of the 36-decanal divinities of the civil year, the other consists of 59 divinities. Parker has suggested that the 59 deities are made up of 48, each representing one quarter of the Moon throughout the 12 lunar months of the lunar year (which together account for 354 days), the remaining 11 each representing one day, and making with the 48 others the civil year of 365 days. The two different series represent the essential duality of the year.

The seven-day week must have been familiar to the Egyptians, through the Jews, from early times. But the first reference to its use in Egypt is by Dio Cassius (3rd century A.D.). The names for the days of the week which have been adopted throughout western Europe are based on the names of the seven known 'planets', arranged in their supposed order of decreasing distance from the Earth —Saturn, Jupiter, Mars, the Sun, Venus, Mercury, the Moon—and are of astrological origin. There was a great development of astrology in Egypt at about the beginning of the Christian era; according to the current astrological beliefs, each hour in succession was consecrated to a different planet, the sequence following the order of their distance. The planet to which the first hour of the day was consecrated was regarded as the regent of that day. If, then, we start with the day whose regent is Saturn, that planet would control the 1st, 8th, 15th, and 22nd hours; the 23rd would belong to Jupiter, the 24th to Mars, and the first hour of the next day to the Sun. Thus is obtained the succession of regents: Saturn, Sun, Moon, Mars, Mercury, Jupiter, Venus, from which the names of the days of the week are derived. In the Teutonic languages, the names of their divinities Tiu, Woden, Thor, and Freya are used instead of their Roman counterparts, Mars, Mercury, Jupiter, Venus; the latter can be recognized in the names used in the Latin languages.

Though the naming of the seven days of the week after the seven planets started in Egypt, whence it spread to Rome and thence throughout western Europe, there is no evidence that the seven-day week was ever in common use in the civil life of Egypt.

II. THE BABYLONIAN CALENDAR

The earliest observations recorded by Ptolemy in his *Almagest*, going back to the year 721 B.C., were observations of eclipses of the Moon made by the Chaldeans, the hereditary priestly caste of Babylon, who acquired a great reputation for soothsaying and forecasting the future by means of the stars. Astrology was first brought by them to a well developed system, and along with its cult there went the study of astronomy, which was unbroken in Babylon for more than 3000 years. The accuracy with which various astronomical periods were determined by the Chaldeans is amazing; many of their determinations were more accurate than those made later by the Greek astronomers [4].

After Cyrus the Great destroyed the Babylonian Empire in 539 B.C., the caste of the Chaldeans gradually lost its splendour. It was at about that time that the Greeks and other western peoples began to become acquainted with the astrology of the east.

Knowledge of the details of the Babylonian calendar is less precise than that of the Egyptian. The calendar seems to have become fairly well fixed late in the third millennium B.C. Its basis was lunar, the beginning of the month being fixed by observation of the first visibility of the lunar crescent; the day, correspondingly, began with sunset. The year normally contained twelve months, but, in order to keep it in phase with the seasons, a thirteenth month was from time to time inserted by repeating a month. There was no consistency, however, in the method of adjusting the length of the year; the intercalary month was inserted at intervals that were quite irregular, being sometimes as short as six months and sometimes as long as six years, and though normally the month to be repeated was the last month of the year it was not unusual for another month to be chosen.

But for the recording of their astronomical observations and for facilitating calculations the very convenient fixed year of 365 days was used. This year may have been derived from the Egyptians or found independently. It appears to have been used in Babylon from the time of the accession of Nabonassar in 747 B.C. and may have been due to him. It thus became possible to determine with ease the exact interval between two observations; the determination of astronomical periods was thereby much facilitated.

The records kept by the Chaldeans of the times and magnitudes of lunar eclipses enabled them to discover the saros or eclipse period, after which eclipses recur. This period was known to them at least as early as the sixth century B.C. They determined its length as $6585\frac{1}{3}$ days. The discovery of the saros made it possible to foretell with considerable accuracy the occurrence of eclipses, although they had no accurate tables of the Sun and Moon. They found the saros period to be equal to 223 lunations. The precise length of 223 lunations is 6585·322 days, so that the error in the Chaldean determination amounts only to about one day in 1800 years or, expressed otherwise, their determination of the mean length of a lunation was in error only by $4\frac{1}{2}$ seconds. The *anomalistic* period of the Moon—the average interval between successive passages through perigee—is 27·55455 days: 239 anomalistic periods amount to 6585·537 days. The *draconitic* period of the Moon—the average interval between successive passages through the nodes of the orbit (the points at which the orbit intersects the ecliptic)—is 27·21222 days; 242 draconitic periods amount to 6585·357 days. Hence, after the interval of a saros, the position of the Moon in its orbit with respect both to the perigee and the nodes is practically unaltered, which accounts for the very close recurrence of the circumstances of individual eclipses after the lapse of a saros period.

It must also have been known to the Chaldeans that the length of the tropical year was $365\frac{1}{4}$ days, for Ptolemy states that after the saros period of $6585\frac{1}{3}$ days (just over 18 years) the Sun was taken to be 10° 40′ to the east of its position at its beginning. Its motion in longitude during this period was accordingly $(18 \times 360°) + 10\frac{2}{3}°$, from which it follows that its motion in longitude through 360° (the tropical year) is almost exactly $365\frac{1}{4}$ days. It is uncertain whether the length of the year was first obtained in this way or whether, from previous knowledge, this length was used to derive the change in the Sun's longitude of 10° 40′. In either case, the length of the tropical year became known.

In 529 B.C. an attempt was made to provide regular intercalations of months by the introduction of an 8-year cycle, consisting of 99 lunations, in which the intercalary months were inserted at fixed places in the cycle; the beginning of each month continued to be fixed by observation. The mean length of 99 lunations is 2923·53 days, that of 8 tropical years is 2921·94 days, while the then accepted length was 2922 days. The error in the supposed equivalence of 8 years to 99 lunations caused the cycle to be abandoned after 25 years, when arbitrary intercalation was resumed.

In 383 B.C. a 19-year system of intercalations was introduced by the Chaldean astronomer Kidinnu (often referred to by the Greek form of his name, Kidenas) in which 19 years were made equal to 235 lunations, seven intercalary months being inserted at fixed places in the cycle, the beginning of each month continuing to be determined by observation. The 19-year cycle had been announced by Meton at Athens in 432 B,C. It is not certain whether the introduction of this cycle in Babylon was made independently of Meton's discovery. After 235 lunations the phases of the Moon recur on the same day of the solar year and nearly at the same time. Such careful records of lunar phases and eclipses were kept by the Chaldeans that it seems unlikely that they could have failed to discover for themselves the 19-year cycle. It should be noted, moreover, that whereas Meton fixed the length of his cycle at 6940 days, the Chaldeans, by determining the beginning of each month by observations of the lunar crescent, tied the length of the tropical year, through the adopted equivalence of 19 years to 235 lunations, to the true mean length of the lunation and so made the mean calendar year equal to 365·2468 days, as compared with the 365·2632 days of the Metonic cycle. The former value is much more nearly correct.

The 19-year cycle of intercalations, introduced by Kidinnu, remained in use throughout the subsequent existence of the Babylonian calendar. It is of interest to note that the determination of the lengths of the year and of the lunation by Kidinnu, together with the system of seven fixed intercalations in 19 years, were taken over by the Jewish calendar and are still used to this day.

The Chaldeans used in their observations both the system of temporal hours, in which the intervals between sunrise and sunset and between sunset and sunrise were separately divided into 12 hours, and the system of equinoctial hours, in which the whole day was divided into 24 equal hours. If an occultation were observed, for instance, the cock of the water-clock was opened at sunset and the quantities of water which flowed out from sunset to the moment of observation and from that moment to sunrise were compared; the time of observation in temporal hours was thus obtained. From the known variation in the length of the temporal hours through the year, the time could then be reduced to equinoctial hours. Alternatively, the amount of water which flowed out from sunset to sunrise was compared with the amount which flowed out from sunrise to sunset, so that a direct conversion from temporal to equinoctial hours was possible.

III. THE GREEK CALENDAR

The basis of the Greek calendar was lunar. The beginning of each month was determined by the first appearance of the crescent Moon in the evening sky after sunset. The length of the month was consequently equal, on the average, to that of the lunation, and was normally either 29 or 30 days. The days were numbered through the month from its beginning, partly to indicate those days which the superstitious had come to regard as lucky or unlucky and partly to ensure that the festival days should not be overlooked in spells of cloudy weather, for most of the Greek festivals were celebrated at definite phases of the Moon.

From very early times the festivals were associated with definite seasons of the year. It must have been evident soon after the lunar month was adopted that the year of twelve months was appreciably shorter than the year of the seasons, because the day of the shortest or longest shadow of the gnomon shifted rapidly from year to year and in three years by more than a month. So a thirteenth month had sometimes to be intercalated. Whether in early times the additional month was always inserted into the same year by the different communities is uncertain, but it can be assumed that there was common agreement from the time of the inauguration of the Olympic games in 776 B.C.

Different communities, however, kept calendars that differed in the season when the year began and in the place in the year at which the insertion of the intercalary month was made. The public authorities decided the length of each month. There was often considerable neglect in keeping the months adjusted to the phases of the Moon, and the manipulation of the calendar became a public scandal. Aristophanes held it up to contempt in *The Clouds*, acted in 432 B.C., when he made the Moon complain that the days were not being kept correctly according to her reckoning.

The adjustment of the calendar to the seasons was made by observing the heliacal rising and setting of bright stars. The zodiacal sign in which the Sun was at any particular season of the year was known; the heliacal rising or setting of any particular sign gave a rough indication of the time of year.

The most ancient division of the Greek year was into three seasons—spring, summer, and winter—which were marked out by natural phenomena such as the arrival and departure of migratory birds. Autumn was first mentioned about 400 B.C. by Hippocrates and other Greek medical writers. Winter began with the heliacal setting of the Pleiades and ended with the spring equinox; spring continued until the heliacal rising of the Pleiades; summer until the heliacal rising of Arcturus; autumn occupied the remainder of the year until the next heliacal setting of the Pleiades.

With the development of civic life and of culture, the system of movable months and years tied to the phases of the Moon became increasingly inconvenient. A growing need was felt for a calendar in which the months and years were not dependent on observation, which was often hindered, moreover, by the weather. The search began for a cycle that should contain as nearly as possible an exact number of years and months. The first step in this direction was taken by Solon about the beginning of the sixth century B.C. He introduced a regular alternation of months of 29 and 30 days, so that 12 months occupied 354 days. This agrees with the length of the lunar year to about 9 hours. But it is 11¼ days short of the length of the year; accordingly, in alternate years a month of 30 days was inserted. The two years together—the short and the long—were 7½ days too long, so from time to time the intercalation was omitted.

A great improvement on the cycle of Solon was effected by the 8-year cycle or *octaeteris* invented by Cleostratus in the 59th Olympiad (about 542 B.C.). In this cycle 8 years were made equal to 99 lunations and to 2922 days. The year contained months of 30 and 29 days alternately. A month of 30 days was intercalated in the third, fifth, and eighth year of the cycle by repeating the sixth month, Poseideon. The average length of the solar year was thus made equal to 365¼ days. As the true length of 99 lunations is 2923·53 days the cycle would rapidly have resulted in a large error in the agreement between the beginning of the month and the new Moon.

Geminus records further improvements made to the cycle to give greater accuracy, but does not state when they were introduced. First, 3 days were added each 16 years, which gave a better approximation to the mean length of the lunation, but only at the expense of a larger error in the year. To obtain a better adjustment to the year, one month of 30 days was omitted in 160 years. With these adjustments 160 years (whose true length is 58 438·8 days) were made equal to 1979 lunations (whose true length is 58 441·0 days) and to 58 440 days. There was accordingly an accumulated error of about one day in 160 years both in the length of the lunation and in that of the year.

It is doubtful whether these modifications of the 8-year cycle were ever used in civil life, for the *octaeteris* was superseded by the 19-year cycle published by Meton in 432 B.C. This was a fixed cycle, in which the length of each month and of each year was determined solely by its place in the cycle and therefore became entirely independent of observation. The months consisted of either 29 or 30 days; in some years there were 7 months of 30 days and 5 months of 29 days, giving a total of 355 days; in others there were 6 months of each length, giving a total of 354 days. A thirteenth month was intercalated after the sixth month, Poseideon, in the 3rd, 5th, 8th, 11th, 13th, 16th, and 19th years of the cycle; these longer years were always of 384 days, the intercalated month having a length of 29 or 30 days according to whether the total length of the other 12 months was 355 or 354 days. The cycle of 19 years (whose true length is 6939·60 days) was made equal to 235 months (whose true length is 6939·69 days) and to 6940 days. The error in this cycle consequently amounts to several hours. The calendar based on this cycle was introduced on the day of the summer solstice (the 13th day of the twelfth lunar month, Scirophorion) in the fourth year of the 86th Olympiad, 27 June 432 B.C., but it is doubtful whether it was ever actually employed for civil purposes.

After the Metonic calendar had been in use by astronomers for a century, a slight modification was proposed by Callippus in order to improve its accuracy. He combined four of the 19-year cycles into a single cycle of 76 years and changed one of the full (30-day) months into a deficient month (29 days), thereby shortening the 76-year cycle by one day. The Callippic cycle thus consisted of 76 years, containing 940 lunations and 27 759 days. It will be seen that this cycle gives for the mean length of the year exactly $365\frac{1}{4}$ days, the value earlier obtained both in Egypt and in Babylon, while 235 lunations are made equal to 6939·75 days, as compared with Meton's value of 6940 days and the true value of 6939·69 days. The modification by Callippus therefore was an appreciable improvement in the lengths both of the synodic month and of the tropical year. The Callippic cycle was made to begin at the summer solstice, the beginning of the first month, Hekatombaon, in the third year of the 112th Olympiad, 28 June 330 B.C. The Callippic calendar was used, by astronomers if not by the general public, for dating events for the next two centuries.

About 130 B.C. a further improvement was devised by Hipparchus. Four Callippic cycles were combined and a single day was again omitted by changing a full into a deficient month. The cycle of 304 years was thus made to contain 3760 lunations and 111 035 days. This gives a length of 365·24671 days for the tropical year and of 29·530585 days for the lunar month, as compared with the true values of 365·24220 days and 29·530598 days. The true length of the lunar month is very exactly represented: the true length of the year is not so closely represented but Hipparchus had obtained from observation a length of 365·24667 days, in close agreement with the mean value in his cycle. It does not seem that any use was ever made of this cycle; it remained merely as a suggested improvement.

The Greeks first adopted the Julian calendar when they adopted the Christian religion. Even so, the lunar months appear to have remained in use by the common people to a much later date. The month of Hekatombaon was displaced from the summer solstice to the autumnal equinox. Probably when the Attic months became solar instead of lunar they were given the old names, the Roman September being called Hekatombaon.

The Athenians numbered their years according to the year of the reign of the hereditary king, and later, in the days of the Republic, after the chief magistrate, who at first held his office for life, but the period was subsequently restricted to ten years. When, later still, the chief magistracy became an annual appointment, the election being either by voting or by drawing lots, the year continued to be named after the holder. This office lasted in Athens until the fourth century A.D., although the Republican régime had long ceased to exist and Greece had come under Roman domination.

For the purpose of dating events in Greek history, the era of the Olympic games is most useful. The Olympic games were founded, according to tradition, by Hercules, but it was not until after the victory of Corobus in 776 B.C. that they were regularly held every four years. The dating of this year has been definitely established through the records of the occurrence of an eclipse. The games were celebrated at about the time of the summer solstice; they lasted five days and ended at the full Moon, which was probably the first after the summer solstice. The year in the Christian era of any event whose dating in the Olympic reckoning is known can readily be found: thus Ol. 112. 3 (the third year of the 112th Olympiad) is $111 \times 4 + 2 = 446$ years later than 776 B.C. (Ol. I. I) and therefore corresponds to 330 B.C. The celebration of the Olympic games was unbroken for 293 Olympiads until the end of the reign of the Emperor Theodosius, A.D. 394, when it was replaced by the cycle of the indiction (p 581).

IV. THE JEWISH CALENDAR

The ancient Jewish calendar was undoubtedly of the lunar type, though nowhere in the Old Testament is there any mention of the lengths of the months (29 or 30 days). That the day began in the evening (probably at sunset) can be inferred from passages in the Pentateuch, such as 'from even unto even shall ye celebrate your sabbath' (Lev. xxiii. 32). It may therefore be assumed that the month began with the first visibility of the crescent Moon in the sky after sunset. The passage in Psalms civ. 19, 'He appointed the moon for seasons', is an indication that the months were determined by the Moon.

The special feature of the earliest Jewish calendar is the emphasis on the week of seven days, with the seventh day as a Sabbath or rest day. The Mosaic commandment that no work was to be done on the seventh day is tied up with the story of the Creation in six days, with the seventh day as a day of rest (Exodus xx. 10–11; Genesis ii. 2–3), so that it is probable that the seventh day had been observed as a day of rest from very early times and certainly throughout the period of bondage in Egypt. It has been conjectured that the seven-day week was in use not merely among the Hebrews but among all the Semitic peoples. From the Jews it was taken over by the Christians and has secured general adoption. The Jews regard the seven-day week as divinely ordained and going back to the time of the Creation; they are in consequence strongly opposed to any scheme of calendar reform that would break the continuity of the week.

The Mosaic law enacted that Abib, the month in which the Israelites came out of Egypt, was to be observed as the first month of the year. It was in this month that the feast of the Passover was to be celebrated and that green ears of corn were to be brought to the priests as the first-fruits of the harvest. The earliest ripening of barley in Palestine is about April, so that the first month of the year must have opened at about the time of the spring equinox. In order to keep the first month at the correct position in the year, it must have been necessary from time to time to intercalate a thirteenth month. The decision whether or not to do so was made by the priests; if it appeared towards the end of the twelfth month that the corn would not be ready to offer as a sacrifice in the following month, then a month would be intercalated. In such a rough-and-ready but practical way the beginning of the year was prevented from drifting through the seasons.

After the captivity the names of the months were changed, the first month being called Nisan. The names of most of the months are given in the later books in the Old Testament, though usually a month is specified by its number in the yearly sequence. They are of Chaldean origin, mostly agreeing with the Syrian names. The beginning of the month was fixed by the appearance of the crescent Moon in the evening; when two trustworthy men had reported to the Sanhedrin in Jerusalem that at such and such a time the Moon had been seen, the new month was declared to have begun. If by the 30th day of any month the new crescent Moon had not been seen, a new month was taken to start on the following day. As it might well happen that because of cloudy weather two or more 30-day months occurred consecutively, it was decided that the year should contain not fewer than four nor more than eight full (30-day) months. Because religious festivals, sacrifices, and so on were fixed with reference to the beginning of the month, the information was spread throughout the country by means of signal fires on the hill-tops or by special messengers. After the captivity a number of Jews remained dispersed in other lands; as the information could not then reach them in time, they were provided with special instructions for beginning a new month. Also, all the important feasts—such as the first and last days of Passover and of the feast of Tabernacles—were duplicated so that, if elsewhere the month was full when in Palestine it was deficient (29-day) or conversely, the feasts would be celebrated everywhere on either the one or the other of the two days.

After the return from captivity, the civil year commenced with the beginning of the seventh month, Tishri; this time was of special importance, because it was on the first day of the seventh month that the law had been read to the people on their return to Jerusalem and burnt offerings offered up on the site of the ruined temple. This brought the Jewish reckoning of the year into agreement with the system that was already well established in Syria. For a time both beginnings of the year were in use; both are, for instance, used in the Apocrypha, though the months are numbered from Nisan. In books of the Old Testament written after the deportation, the years of the kings and the months of the festivals are generally reckoned from Nisan. The older beginning of the year gradually fell into disuse, however.

In more recent times, after the destruction of Jerusalem by Titus and the dispersion of the Jews, the empirical calendar, in which the beginning of each month was fixed by observation, was replaced by one based on fixed rules. The date of the introduction of this fixed calendar is not known, but it is generally thought to be about the fourth century A.D. Its basis is the 19-year cycle introduced into Babylon by Kidinnu, containing seven intercalary months, and therefore incorporating a mean length of the synodic month of 29·530594 days and a length of 365·2468 days for the year. The beginning of the month of Tishri in this calendar is determined by complicated rules, designed to prevent various festivals and solemn days from falling on incompatible days. The normal ordinary year consists of months of 30 and 29 days alternately, giving a total of 354 days. The normal embolismic or leap year contains an extra month of 29 days, inserted after the sixth month, Adar, and known as Veadar, but the length of Adar is then increased from 29 to 30 days, so that the year contains 384 days. The embolismic years of each 19-year cycle are the 3rd, 6th, 8th, 11th, 14th, 17th, and 19th.

Because of the special rules already referred to, the second month, Hesvan, may sometimes require to have one day more than in an ordinary year and the third month, Kislev, may require to have one day less. Consequently, an ordinary year may have 353, 354, or 355 days and the embolismic year may have 383, 384 or 385 days.

The insertion of Veadar in the embolismic year ensures that the Passover, on the 15th day of the following month Nisan, is kept at its proper season, which is the full Moon after the vernal equinox. It always precedes the following new year by 163 days. Pentecost always precedes the new year by 113 days.

In our present Gregorian calendar, the epact is the age of the Moon of Tebet, the fourth month of the Jewish calendar, and so represents the day of Tebet corresponding to 1 January. The approximate date of the beginning of the Jewish year can be obtained by subtracting the epact from 24 September after an ordinary year, or from 24 October after an embolismic year. It can range from 5 September to 5 October.

The Jews employ an era of the Creation whose date is taken as 7 October, 3761 B.C. In this era the Jewish year 5718 began on 26 September 1957.

V. THE ROMAN CALENDAR

The calendar which is now used throughout the whole of the civilized world had its origin in the local calendar of the city of Rome, the beginning of which is lost in obscurity. It is stated by authorities such as Macrobius and Censorinus that Romulus, at the foundation of the Roman state, instituted a year containing ten months and comprising 304 days. Six of these months, namely April, June, Sextilis, September, November, December, each contained 30 days, and the other four, March, May, Quintilis, and October, each contained 31 days. The year began with March, as is proved by the names of the last six months (Quintilis, Sextilis, etc.).

The origins of the names of the first four months are uncertain: March is supposed to have been named in honour of Mars, the father of Romulus, and April after Aphrodite or Venus, the progenitress of the Ænean race. May and June are supposed to have been named respectively after the *majores* or elders, and the *juniores*. Many other origins have been suggested: April, for instance, from *aperire*, the month when the earth is awakening from its winter torpor though, if the year originally contained only 304 days, the months would have drifted through the seasons so quickly that this derivation could not be correct. Ovid affirmed in his *Fasti* that the original year contained ten months, but was not certain about the derivation of the names of the first four months.

Probably, as Eutropius believed, the Roman year before the time of Núma had no definite system. It is reasonably certain that the months were lunar and did not have the fixed numbers of days mentioned above. Numa is supposed to have added 2 months (51 days) to the year, making a total of 355 days. January (named from the god Janus, facing backwards and forwards) now began the year, and February (from the god Februus, who presided over ceremonies of purification) preceded March, which became the third month.

According to Macrobius and Censorinus, Numa took 1 day from each of the 6 months of 30 days, as the Romans had a superstitious dislike of even numbers;

these 6 days, with the 51 additional days, were divided between January (29 days) and February (28 days). Thus January, April, June, Sextilis, September, November, and December each had 29 days; March, May, Quintilis, and October continued to have 31, while February had 28. The year of 355 days strongly suggests a lunar calendar, as it exceeds 12 lunations by only 0·63 days. The difference between the length of this year of 355 days and the solar year was adjusted by the intercalation of a month, when it was considered necessary. This intercalated month normally alternated between 27 and 28 days, but adjustment to the proper seasons was obtained by omitting the intercalary month from time to time.

The intercalary month was inserted after 23 February. Whatever may have been done in earlier times, in later historical times the last five days of February, which should have followed the end of the intercalary month, were omitted. The actual number of additional days in the intercalary years was therefore either 22 or 23. The calendar had consequently worked free from the Moon and became purely solar. It is uncertain when this occurred, but it was certainly before 400 B.C. The normal sequence of days in four successive years was 355, 377, 355, 378, giving an average length of the year of 366¼ days, about one day too long.

The days of the month were enumerated backwards from the next following Kalends (1st of month), Nones (5th of month, except for the 31-day months when it was the 7th of month) or Ides (13th of month, except for the 31-day months when the 15th of month). Thus the day after the Ides, for instance, would be expressed as 17 days before the Kalends of the next month.

The intercalary month was normally inserted in alternate years. The actual regulation of the calendar was under the exclusive control of the College of Pontiffs, as a matter of religious importance, and was not always done honestly; the calendar was often manipulated for political or personal ends. When Julius Caesar became Pontifex Maximus in 63 B.C. intercalation was so often neglected that by 47 B.C. the months had drifted considerably from their proper seasons, causing the celebration of various festivals to come at the wrong times. January, which should have followed the winter solstice, occupied the season of the year that should have been occupied by October.

Julius Caesar accordingly decided upon a reform of the calendar and called in the astronomer Sosigenes of Alexandria for advice and assistance. The first step was to correct the error into which the calendar had fallen. The year corresponding to 46 B.C. was given the usual intercalation of an additional 23 days, and two further months, amounting together to 67 days, were inserted between November and December, in order to bring the Kalends of 45 B.C. to their proper position, corresponding to 1 January; this year, known as 'the year of confusion', consequently contained 445 days.

On the advice of Sosigenes the mean length of the year was fixed at 365¼ days; to achieve this, it was decreed that the normal length of the year should be 365 days but that an additional day should be inserted every fourth year. The lengths of the months were fixed at the present durations, which have never since been altered. The extra day in a leap year was obtained by repeating the sixth day before the Kalends of March (on which occurred the feast of Terminalia), and so it became known as *ante diem bis sextum Kalendas Martias* or simply *bissextum*, whence we derive our word bissextile for leap year.

In the new calendar the months of March, May, Quintilis (July), and October, which already had 31 days, remained unaltered in length. They retained their Nones on the 7th and their Ides on the 15th day of the month. January, Sextilis, August, and December were increased in length from 29 to 31 days; their Nones remained on the 5th and their Ides on the 13th day, the days that were added being placed at the end of the month so that the religious festivals connected with the Nones and Ides, which took place on fixed days, should not be changed. In 44 B.C. the name of Quintilis was altered to July (*Julius*) in honour of Julius Caesar.

The essential and important feature of the reform was that the calendar year became purely solar. The months were given definite lengths, the same from year to year (except for February) and there was no attempt to relate them to the phases of the Moon. The seasons were expected to retain their places in the calendar without change; farmers could therefore plan their work by the calendar without having to consider the phases of the Moon.

The pontiffs misunderstood the directions for the intercalation and proceeded to add one day every third year instead of every fourth. In consequence the year 8 B.C. began three days too late. When this was discovered, Augustus directed that it should be corrected by suspending further intercalation until the error had been eliminated. From that year, A.D. 8, the Julian calendar remained in force without further alteration until its reform by Pope Gregory XIII in A.D. 1582. The name of Sextilis was changed in the year 8 B.C. to August (*Augustus*) in honour of the emperor.

The years in the Roman calendar were commonly designated by the names of the consuls and changed when the new consuls took up their office. In the early days the date of entering office was frequently changed, but about 222 B.C. it was fixed at 15 March (the Ides of March). March was then the first month of the year. In 153 B.C. the date was changed to 1 January, which then became the first day of the new year; this beginning of the year was never afterwards changed. In the eastern provinces, however, the years were often reckoned from the accession of the reigning emperor, the second year of his reign being counted from the first new year's day (which varied from province to province) following his accession.

The dates of events in Roman history are usually indicated by reference to the supposed date of the foundation of Rome. The letters A.U.C.—an abbreviation of *anno urbis conditae*—are used to express dates in this era. The generally accepted date for the conventional beginning of the era is 753 B.C., corresponding to Olympiad 6. 4. This date, ascribed to Varro, was supported by Cicero and Plutarch and was adopted by Censorinus.

The Christian era, in which years are reckoned from the supposed date of the Incarnation, was introduced by the Scythian monk Dionysius Exiguus about A.D. 530. He based the date of the Incarnation on the widespread tradition that Christ was born in the 28th year of the reign of Augustus; he assumed the beginning of the reign of Augustus to have been 727 A.U.C., which is now known not to be correct. Dionysius constructed a table of the dates of Easter from A.D. 532 to A.D. 626, in which he used the new era. From him it was adopted by Bede, and from Bede by western Christendom generally.

VI. THE GREGORIAN CALENDAR

The mean length of the year of the Julian calendar is 365·25 days, which is 0·0078 days or 11 min 14 sec longer than the tropical year. This difference causes the seasons to drift gradually backwards in the calendar. The discrepancy is small; it first became noticeable in connexion with the observance of Easter.

In A.D. 325 the General Council of Nicea had dealt with the date of Easter to ensure, amongst other things, that the observance by the various Christian communities should be on the same date. In the framing of the tables for the dates of Easter in different years, it was assumed that the spring equinox was on 21 March, though it actually fell on the evening of 20 March. The date of Easter, derived from that of the Jewish Passover, depends upon the date of the occurrence of the first full Moon after the vernal equinox. As the centuries passed, the calendar date of the vernal equinox fell progressively earlier and there was in consequence doubt as to the correct date for the celebration of Easter.

The Council of Trent, which assembled in 1545 and continued its sittings for 18 years, authorized the Pope to take the matter in hand. By that time the vernal equinox had receded to 11 March. When Gregory XIII became Pope in 1572 he found various proposals, which had been submitted to his predecessors, awaiting him. The plan which was most favoured was one proposed by Aloysius Lilius, a Neapolitan physician. This proposal was submitted to various Christian princes and learned academies for comments, and a commission of mathematicians and chronologers was appointed to consider it. In 1582 the Pope published a bull instituting the revised calendar.

It was ordained that the day after 4 October 1582 should be called 15 October, in order to restore the vernal equinox to 21 March, the date assigned by the Council of Nicea. In future the intercalary day was to be dropped in those centurial years that were not divisible by 400, in order to maintain a more exact correspondence between the calendar and the tropical years. Certain changes were made at the same time in the rules for fixing the date of Easter.

In the Gregorian calendar there are 97 leap years in 400 years, so that the average length of the calendar year is 365·2425 days. The cumulative error will amount to 2 days 14 hours 24 minutes in 10 000 years. A more exact agreement between the calendar and tropical years would be obtained if the years divisible by 4000 without remainder were not counted as leap years; there would then be 969 leap years in 4000 years, giving an average length of the calendar year of 365·24225 days, which is too great by about 4 sec.

The new rules for fixing the date of Easter which were incorporated into the Gregorian reform imply a mean length of the lunation that is in error by only the millionth part of a day. These rules determine the date of a hypothetical full Moon, whose motion is closely in agreement with the mean motion of the actual Moon. As the tables ignore the inequalities of the actual motions of the Sun and Moon, the date of the Easter full Moon may differ by a day from the actual date of full Moon. This can occasionally result in the ecclesiastical full Moon occurring after the vernal equinox with the true full Moon occurring before it, and conversely. The tables, which are based on the 19-year cycle, fix the full Moon for a definite calendar date for the whole world, whereas the true full Moon occurs at a definite instant which may not be on the same calendar date all over the world.

The Gregorian calendar was adopted in Italy, Spain, Portugal, France, and Poland in 1582, by the German Catholic States, Holland, and Flanders in 1583, and by Hungary in 1587. Its adoption was long delayed by the Protestant countries. The German and Dutch Protestant states and Denmark adopted it in 1700, Britain and the British dominions in 1752, Sweden in 1753, Japan in 1873, China and Albania in 1912, Bulgaria in 1916, Soviet Russia in 1918, Rumania and Greece in 1924, and Turkey in 1927.

In Britain the Gregorian calendar was officially introduced by the Calendar

New Style Act (1750) under which Act it came into operation in 1752, the day following 2 September being designated 14 September (but without interruption of the continuity of the week). There was considerable opposition from the common people, who rioted with the cry: 'Give us back our eleven days.'

At the same time the official date of New Year's Day in England was changed from 25 March to 1 January, which date had already been adopted in Scotland in 1600. English dates between 1 January and 25 March before 1752 are commonly given with both of the alternative years; it should be noted, however, that, for the purpose of intercalating the extra day in February before 1752, the year had been treated in England as though it had commenced on 1 January. Some customs dependent on the calendar remained unchanged and have persisted to the present day: thus the official date for the ending of the government financial year is 5 April, corresponding to 24 March, the last day of the year in the Julian calendar style.

The different reckonings of the beginning of the year are known as styles. In Italy down to the eighteenth century the years of the Christian era began in the Venetian style on 1 March, in the Pisan style on the preceding 25 March, and in the Florentine style on the following 25 March. In England the Nativity style, beginning on 25 December, was used in the early Middle Ages; it was superseded by the Annunciation style, beginning on 25 March (Lady Day), in the fourteenth century. The style beginning on 1 January is known as the Circumcision style. The word 'style' is also used in a somewhat different sense, dates in the Julian and Gregorian calendars being often referred to as 'old style' and 'new style' respectively.

VII. THE ISLAMIC CALENDAR

Muslims use a calendar for religious purposes that is purely lunar and has no connexion with the solar year. The year consists of twelve lunar months, the beginning of each month being determined by observation of the crescent of the new Moon in the evening sky. Different beginnings of the month may consequently be used by neighbouring communities. As a result there is uncertainty about the precise day of any date given in this calendar unless the day of the week is also specified; this is usually done in important documents.

The era of the calendar is dated from the first month preceding the flight (*hijra*, hegira) of Muhammad from Mecca to Medina, namely Thursday, 15 July, A.D. 622, and the calendar commences on the following day. It is known as the era of the Hegira (A.H.).

The new year of the Islamic calendar retrogrades through the seasons in about

$32\frac{1}{2}$ years. For astronomical purposes the months are fixed by rule and not by observations. The months have 30 and 29 days alternately, except the twelfth month which may have either 29 or 30; in a cycle of 30 Islamic years 19 are common years of 354 days and 11 are intercalary years of 355 days. The years of the cycle numbered 2, 5, 7, 10, 13, 16, 18, 21, 24, 26, 29 are the intercalary years.

This calendar makes 360 lunations equivalent to 10 631 days; their real duration is 10 631·015 days, so that the error is extremely small.

VIII. THE JULIAN PERIOD

For many chronological purposes and for various purposes in astronomy the Julian Period, invented by Scaliger (1484–1558), is very useful. This period is formed by the continued product of the cycle of the Moon (19 years), the solar cycle (28 years, after which, in the Julian calendar, the days of the year recur on the same days of the week), and the cycle of the indiction (a non-astronomical cycle of 15 years, which took its origin in a provincial census for taxation in Egypt about A.D. 300 at 15-year intervals). Its length is thus $19 \times 28 \times 15 = 7980$ years. In this period no two years can be expressed by the same numbers in all three cycles. All these cycles began on 1 January in the Julian calendar in 4713 B.C., so that one Julian period covers all dates in recorded history and is therefore for some purposes more convenient than an era whose epoch lies in historical times.

The year of the Julian period is now little used. On the other hand, the numbering of days in this period continuously from 1 January 4713 B.C. is very convenient and is much used for calendarial purposes and in astronomy. If the Julian days of two events are known, the exact number of days between them is at once ascertained, without complication of changes of calendar and so on that may have intervened. The Julian day begins at noon. Julian day 2 435 840 began at Greenwich mean noon on 1 January 1957.

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22

PRECISION INSTRUMENTS: TO 1500

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with a section (VII) on Hero's instruments by A. G. DRACHMANN

I. THE IDEA OF THE PRECISION INSTRUMENT

THE development of precision instruments is, in the main, part of the larger story of astronomy. Man's early interest in the regularity of celestial motions and their connexion with seasonal changes of his environment is one of the most important factors in the cultural life of primitive civilizations. There is no need to tell here how the Sun and the Moon, planets, eclipses, the heliacal rising and setting of bright stars, and other astronomical phenomena became endowed with mystical significance. Clearly there was a need to formulate these regularities and to predict the periodic phenomena that were so vital to seasonal occupations in daily life and to ritualistic practice in religion.

To formulate such astronomical theory it is essential not merely that there should be qualitative observation of the heavens: there must also be accurate measurement of the position of stars and planets at definite times. Much is possible without the use of any but the most primitive aids, such as a plumb-line held in front of the eye (cf the *merkhet*, vol I, figure 47), a string held out so that it appears to draw a straight line in the sky from one star to another, and the marking of a shadow cast on the ground by a pillar or a high building. Using such means alone, as far as we know, the Babylonians had by the second millennium B.C. built up an accurate *corpus* of measurements and a series of empirical rules for predicting phenomena with very great accuracy.

The Sun and Moon seem quite large objects, and an error of observation or prediction similar in magnitude to their diameters would be out of the question for even approximate use; this sets a lower limit to accuracy amounting to the angular diameter of those bodies—about 30 minutes of arc. On the other hand the physiology of the eye prevents it from distinguishing objects if they are separated by less than about one minute of arc, and though it is actually possible to sight a single star with great precision, this may be taken as a useful upper limit to the accuracy obtained in naked-eye astronomy. All astronomers from the Babylonians up to Tycho Brahe were imprisoned between these limits of attainment. From Alexandrian times until the end of the Middle Ages one may safely assume that the accuracy attained lay at about 5 minutes of arc for angle-measurements, 20 seconds of time when estimated by the diurnal rotation, and $2\frac{1}{2}^\circ$ of terrestrial longitude when this was found by eclipses or other methods involving lunar positions (table I).

The goal of devising astronomical theories that would agree with observations within such a degree of fineness was eventually attained in most particulars by the Alexandrian astronomers from Hipparchus (second century B.C.) to Ptolemy (A.D. 150). Once the theories had been devised, and even indeed while they were in the course of construction, it became necessary to make observations and measurements of similar accuracy, but in circumstances where the simple techniques of plumb-line, shadow, and string were inadequate. This led to the invention of a series of instruments for the measurement of time and of angular distance. Results obtained by the use of these instruments were fed into the theory, resulting in an increase of accuracy and a demand for instruments of even greater precision and wider variety.

TABLE I

Orders of Accuracy in Astronomical Observation

	Casual estimation Error corresponds to apparent size of Sun or Moon	*Reasonably good*	*Best probable* Error corresponds to resolving power of the eye
Angular accuracy (minutes of arc)	30′	5′	1′
Radius of a divided circle on which the angular accuracy corresponds to an error of 1 mm of scale .	12 cm	72 cm	360 cm
Time occupied by a diurnal rotation of the heavens through an angle corresponding to the angular accuracy . . .	2 min	20 sec	4 sec
Accuracy of a determination of terrestrial longitude using lunar measurements made with this order of error*	15°	2° 30′	30′

* This follows from the fact that the Moon revolves only once in some 28 diurnal rotations of the heavens. The error of a determination of terrestrial latitude is the same as the angular accuracy.

Such continuous progress of supply and demand put a great strain on technical skill and inventiveness. An angle of 5 minutes—one-sixth of the apparent diameter of the Sun—is readily discernible in astronomical use, but for terrestrial purposes it subtends a distance of only 1 mm on a divided circle 1½ m in diameter. An instrument must certainly be very large, carefully and closely divided, perfectly jointed, and made quite stable in order to secure this required accuracy. The story of precision instruments is that of a succession of men applying themselves to attaining these ends.

II. SCHOOLS OF INSTRUMENT-MAKERS

The first great wave of instrument-making was due to the Alexandrian astronomers; it reached a peak with the work of Ptolemy, continued to develop slowly for a few centuries, and then perished with the rest of the world of classical science. Very little of the theory or the knowledge of instruments was transmitted to the Byzantine Empire, though a notable exception is provided by the fortunate preservation of two important texts on the astrolabe and a unique specimen of the instrument itself (p 603).

When Greek science passed to the Arabic-speaking peoples, it was astronomical theory, probably more than anything else, that excited them and called forth the greatest activity. More than six centuries had elapsed since Ptolemy's *Almagest* was composed, and the small secular motions of the heavenly bodies had accumulated sufficiently to be perceptible. The need for correcting the newly recovered theory, and the opportunity to make it more perfect by re-estimating the secular terms, must have been a very attractive incentive to further work. One finds indeed a brilliant series of advances, each including the establishment of an observatory with special instruments, and leading to the publication of a new set of astronomical tables with canons explaining their use and improving the existing theory. The most important of these observatories were those founded at Baghdad by Al-Ma'mūn (813–33), at Cairo in 966 by Al-Ḥākim, at Toledo by Al-Zarqālī (*c* 1029–87), at Marāgha by Nāṣir al-Dīn al-Ṭūsī (1201–74), and the great observatory founded at Samarkand by Ulugh Beg about 1420. A notable feature of this activity is the appearance for the first time of men who seem to have specialized as instrument makers and designers. There is, for example, Al-ʿUrdī who worked for Al-Ṭūsī at Marāgha, and there are many craftsmen and even dynasties of craftsmen to whom the description *al-asṭūrlābī*, 'the astrolabist', is applied.

The revival of astronomy in Europe dates from the translation of the *Almagest*, first from the Greek in 1164 and then from the Arabic in the popular version of Gerard of Cremona in 1175. The Toledo tables of Al-Zarqālī were translated in 1187, and were in common use from the beginning of the thirteenth century until they were displaced by the Alfonsine tables (1274), which reached the great university centres of Oxford and Paris by the beginning of the fourteenth century. Both these sets of tables with their accompanying canons (that is, explanations, and texts on instruments) gave rise to much activity in the construction and use of astronomical instruments. Many new instruments were devised and probably made by such scholars as John of Linières (fl Paris, 1320–50), and Richard of Wallingford (1292?–1335) (tailpiece) and other astronomers of Merton College, Oxford. By the end of the fourteenth century the second burst of interest had lost its impetus in England and in France, without the establishment of any great observatories or any tradition in the craft of instrument-making. The beginnings of the great renaissance of instrument-making are to be found in Germany during the latter half of the fifteenth century. One of the first indications of the existence of specialist craftsmen is the purchase by Cardinal Nicolas of Cusa (Cues, on the Moselle) of three instruments and fifteen books on astronomy during a visit to Nuremberg in September 1444. The instruments, which are still preserved at Cues, were a large wooden sphere, a *torquetum* (p 593), and an astrolabe.

Soon after this there is more definite information about the pre-eminence of Nuremberg in scientific instruments, for when Regiomontanus settled in the city in June 1471 he wrote that he had chosen the place 'because I find there all the peculiar instruments necessary for astronomy, and there it is easiest for me to keep in touch with the learned of all countries'. Both reasons were due to the fact that Nuremberg straddled the great trade-route of Europe that ran from Italy to the Low Countries and carried the merchandise (and manuscripts) of the world. The structure of the city-state and its highly organized guild craftsmen had already made it a centre for the skilled metal-work needed in the construction of fine instruments. Although Regiomontanus records a favourable state as already existing on his arrival, it was his own life-work that made the city so famous for its scientific craftsmen, and caused the craft to spread to Augsburg and indeed to the whole surrounding area. Throughout the sixteenth century, and until the Thirty Years War, Nuremberg and Augsburg produced instruments of considerable ingenuity and of such exquisite craftsmanship that many have been preserved as fine works of art; they are frequently signed and dated by the maker, and they enable the development of the craft to be chronicled in detail from this period onwards.

In Italy, too, there was some activity, particularly in the latter part of the century, but there does not seem to have arisen any school of workmanship comparable with that in Germany during the same period.

Some of the finest extant specimens of astrolabes and other instruments were made at Louvain by Walter Arsenius and other members of his family. The workshop had been inspired by the astronomer Gemma Frisius (an uncle of Arsenius) and by Gerard Mercator. Unfortunately, after a fairly short life the workshop was dismantled, and unfinished instruments were scattered over Europe owing to the 'Spanish Terror' that devastated the Low Countries in 1578 and thereabouts.

In England, some instrument-making had been introduced by Nicolas Kratzer, a Bavarian who lectured at Oxford on astronomy. Some of his instruments can be seen in the portrait of him by Holbein, and again in 'The Ambassadors' by the same artist. The first regular craftsmen seem to have flourished under the aegis of John Dee (1527–1608) and Leonard Digges (*c* 1550), and at a time when there was great interest in England's maritime adventures and explorations. The first mathematical instrument-maker here was Thomas Gemini (fl 1524–62) who came from Lixhe near Liége and settled at Blackfriars; he had great skill in the engraving of brass instruments and had indeed already established his reputation by engraving the plates for the 1545 English edition of Vesalius. Soon after him came the first Englishman to take up the craft, namely, Humfray Cole (1530?–91), an engraver and die-sinker who worked at the Mint and was connected with the Mineral and Battery Works (1565) which made sheet brass available in England for the first time. The wide range of Cole's surviving instruments is as remarkable as their fine engraving and ingenious construction. Within a few generations from the time of Cole the number of suppliers of mathematical instruments had increased prodigiously, and the range of their products had extended from astrolabes, sun-dials, and quadrants to include devices for surveying and gauging, as well as a series of instruments designed for the performance of 'philosophical experiments' (p 636).

III. OBSERVATORY INSTRUMENTS

The only full account of the instruments used by the Alexandrian astronomers is contained in the *Almagest* of Ptolemy (second century A.D.) and in the commentaries on this work by Proclus, Theon, and Pappus. In general it is impossible to tell whether the instruments and the minor variations on them described by the commentators were devised by Ptolemy himself or by others. Some forms must have been known by Hipparchus (second century B.C.), and some may be of even greater antiquity. It is clear, however, from the designs of the instruments that they are at best only a stage or two removed from the earliest *ad hoc* devices which replaced the primitive line and plumb-bob expedients. Each instrument has been devised for a specific purpose, a single type of observation. There is no indication of a move towards the economy and convenience of designing an instrument that might be used for a variety of purposes. Furthermore, the limitations of technique in constructing the instrument are everywhere apparent. Wood or stone is used whenever possible, and where metal is employed it takes the form of armillae constructed from strips of bronze rather than sheets or disks which might otherwise have been preferable.

(a) *The equinoctial* (*or equatorial*) *armillary*. In the *Almagest* Ptolemy describes how Hipparchus used this instrument to determine the dates of vernal and autumnal equinoxes at Alexandria. It consists simply of a large ungraduated bronze ring, set rigidly on a masonry base and adjusted exactly in the plane of the celestial equator (figure 343 C). When the Sun is north or south of the equator the fore-edge of the ring casts no shadow on the hind-edge, but at the equinoxes, where the ecliptic[1] crosses the equator, the shadow will fall precisely on the inner surface of the lower part of the ring. It is desirable to make the ring as large as convenient (Theon says it should be at least 2 cubits in diameter[2]), and the accuracy depends entirely on the lack of distortion of the ring and the accuracy with which it is set in the equatorial plane. Ptolemy is explicit on this point and mentions that the older and larger of the two equatorial armillaries in the principal palaestra at Alexandria was no longer reliable owing to distortion and the shifting of its placement. He also notes that an error of observation of only 6 minutes (corresponding to a shadow movement of about 1½ mm in a 2-cubit instrument) causes an error of about 15 minutes in the Sun's longitude in the ecliptic; this implies an error of 6 hours in determining the date of the equinox. The public site of the Alexandrian instrument is a reminder of the importance of equinoctial observations for ritualistic and calendrical purposes.

(b) *The plinth*. This is one of two instruments described in the *Almagest* and used to determine the midday altitude of the Sun; such observations made at the periods of winter and summer solstice enabled the astronomer to determine the obliquity of the ecliptic and the latitude of the place of observation. The instrument consists of a single block of stone or wood, set on the ground and carefully levelled by thin wedges driven underneath (figure 343 A). One face of the block in the plane of the meridian is smoothed with set-square accuracy, and two cylindrical pegs are set at the top and bottom of the southern edge of this face. The upper peg is used as a gnomon to cast a shadow upon a graduated quadrant of arc engraved on the face. This peg also supports a plumb-line which should fall exactly on the lower peg when the plinth is correctly levelled. Because the peg casts a wide shadow it is necessary to measure both edges on the scale and take the average of the readings. A serious disadvantage of this form of the plinth is that the Sun can cast a shadow on the face of the plinth only before noon or after noon, according to whether the surface looks due E or due W; this makes it difficult to judge the moment of true noon, when readings must be taken. This objection was met in later ages by the replacement of the peg and shadow device by a pivoted arm carrying a pair of sights. In this form, as the 'mural quadrant', it was used by Tycho Brahe (1546–1601).

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[1] The apparent path of the Sun's annual rotation against the background of the fixed stars.

[2] The cubit originated in the length of the forearm. 1 cubit = about 45 to 55 cm.

(c) *The meridional armillary.* As an alternative to the plinth, and for the same purpose of determining the meridian altitude of the Sun, this instrument is described in the *Almagest* and also by Proclus (fifth century A.D.) in his *Hypotyposis astronomicarum positionum.* It consists of an accurately made and graduated bronze ring, mounted on a pillar and set vertically in the plane of the meridian[1] (figure 343 B); Ptolemy does not give dimensions, but according to Proclus the ring should be not less than ½-cubit in diameter and graduated every 5 minutes of arc. Even with a ring one cubit in diameter this would correspond to the very unlikely fineness of marking of about 3 divisions in the space of 1 mm. Inside the fixed ring, a smaller concentric ring fitted closely, its sides flush with the outer ring, but with sufficient play to enable it to turn freely in its meridional plane; small catches prevented it from falling out of its frame. At the opposite ends of a diameter of the rotating ring, little plates serving as sights were mounted perpendicularly to the plane of the rings. Proclus represents these plates as having holes for seeing through, but according to Ptolemy and Theon the plates are whole, and a sight was taken by allowing the shadow of the upper plate to fall exactly on the lower. Pointers at the ends of the diameter enabled a reading to be taken on the graduated arc of the fixed circle, and a plummet suspended from the apex of the ring allowed the instrument to be levelled. It was set in the meridian plane by aligning the sights against a meridian line marked on the ground below the instrument. The usefulness of the meridional armillary must have been severely limited by its comparatively small size; it was also impaired by the unsound mechanical construction. A friction-fit between two rings is particularly sensitive to any deformation, and the necessary free play of the movable ring can cause considerable error in taking readings. It is significant that the use of the alidade[1] with two sights mounted on it—a far superior device—is not employed by Ptolemy in these instruments.

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[1] The plane containing the observer, the north and south poles, and the zenith. Hence the meridian altitude of a body is its altitude in degrees as it passes through this plane.

(d) *The parallactic instrument* (*Ptolemy's rulers* or *triquetrum*). This is perhaps the most serviceable of Ptolemy's instruments, and the only one used in similar form by subsequent astronomers. Copernicus (1473–1543) used it for his observations, and his 8-ft-long instrument eventually passed as a cherished relic into the hands of Tycho Brahe. Its use, as described in the *Almagest*, was for determining the zenith[2] distance of the Moon at its meridian passage, but it could also be employed for measuring the meridian transits of the fixed stars.

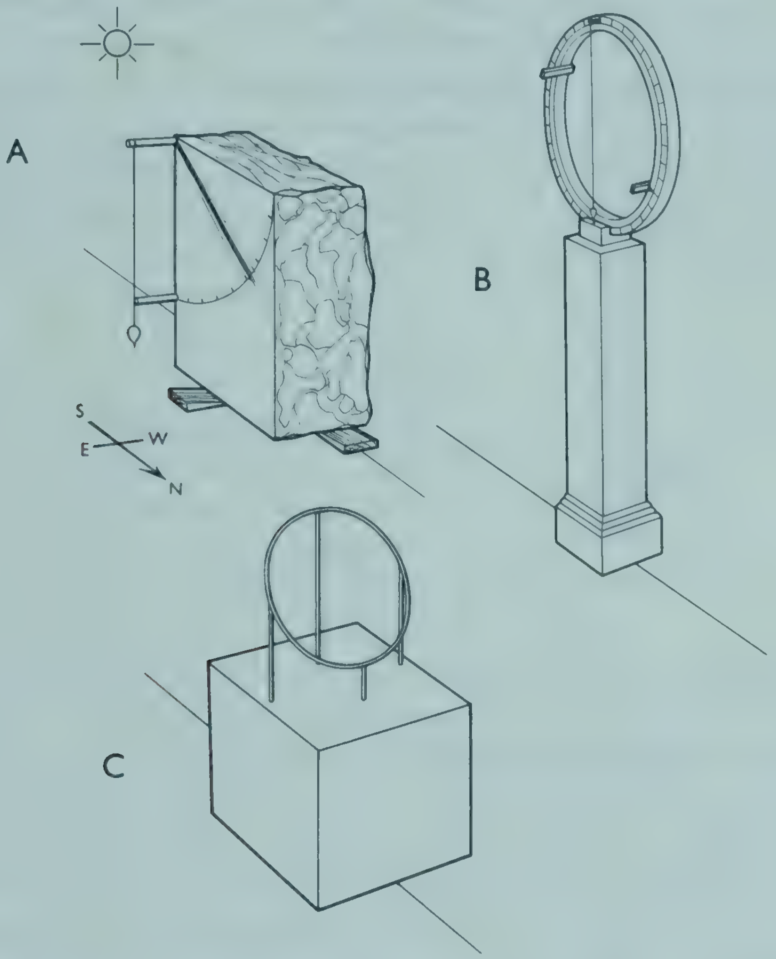

FIGURE 343—*Astronomical measuring instruments described by Ptolemy.* (A) *the plinth;* (B) *the meridional armillary;* (C) *the equatorial armillary.*

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[1] The diametrical or radial arm of circular measuring-instruments, pivoted at the centre and marking at its ends a position on the circle.

[2] The point on the celestial sphere directly above the observer's head. Hence zenith distance is the complement of altitude.

It consists of a vertical post at least 4 cubits high (figure 344); at the top of the post is pivoted an alidade containing a pinnule at the lower end and a larger hole at the upper; at the bottom of the post is pivoted a thin lath of wood.[1] As with the other instruments, a plumb-line is used to ensure that the main post is upright. A pin or pointer is placed near the free end of the alidade so that its distance from the pivot is exactly equal to the distance between the upper and lower pivots on the vertical post. Readings are taken by sighting the Moon through the pinnule so that it is just framed by the larger hole in the upper sight, and then marking the position of the pin or pointer along the thin lath. The distance along the lath from its pivot to the mark was then a measure of the chord of the angle between the alidade and the vertical; the angle itself could be read off from the tables of chords, which were readily available. The instrument was adjusted so that the alidade swung in the plane of the meridian, but there must have been considerable flexure in the alidade and in the vertical post, and together with any slight play at the pivots this would make it a rather inaccurate device.

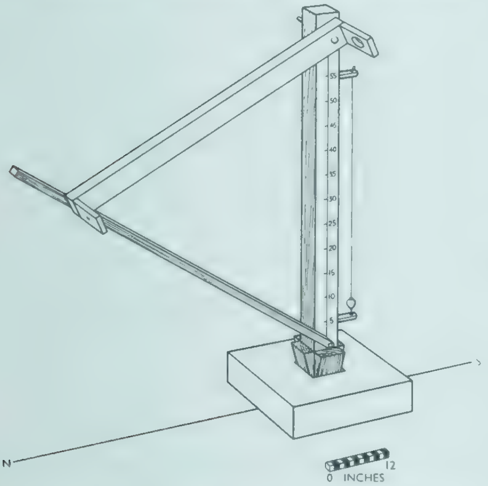

FIGURE 344—*The* triquetrum, *or Ptolemy's rulers.*

In the form of instrument described by Ptolemy and by Pappus, the lath itself is not graduated; after taking an observation the lath is swung up and compared against a scale engraved on the upright post. This has the advantage of protecting the engraved scale from damage, and also enables the reading to be taken at leisure when the sighting has been satisfactorily completed. In spite of this it is clearly more accurate to avoid transferring the readings to another scale, and the step of graduating the lath was taken eventually by Al-Battānī (*c* 858–929).

The vital point of the parallactic instrument is that it employed only a simple graduation along a straight line and avoided the accurate division of a circular arc, a troublesome and tedious procedure. Even though it was necessary to consult a table of chords for each observation, the use of the parallactic instrument was more convenient and probably more accurate than would have been the graduations of a circular arc of similar size. Furthermore, the parallactic instrument could be folded flat and transported without damage far more easily than any other observational device of similar radius and accuracy.

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[1] The post, alidade, and lath are the 'three rods' implied by the name *triquetrum*.

(e) *The four-cubit dioptra.* This instrument is mentioned in the *Almagest* as a device described by Hipparchus and used for measuring the apparent diameter of the Sun or the Moon. Ptolemy does not give a description, but fortunately one is provided in the commentary by Pappus. The instrument consists of a rod (probably wood) rectangular in cross-section and at least 4 cubits long (figure 345). A dove-tailed groove runs the length of the rod on one of its faces, and into this groove fits a small slider carrying a small perpendicular prism. The observer looks through a pinnule in a block fixed to one end of the rod, and moves the slider back and forth until the prism just covers the apparent solar or lunar disk. The angle subtended by the disk can then be found from the known width of the prism and its distance from the sighting-pinnule. It is worth noting that the prism, if it is to cover the solar disk at 4 cubits, must be only about 1½ cm in width. In another form of the instrument, the prism is replaced by a plate having two small sighting-holes; this would probably be more convenient as reducing the direct glare when observing the Sun.

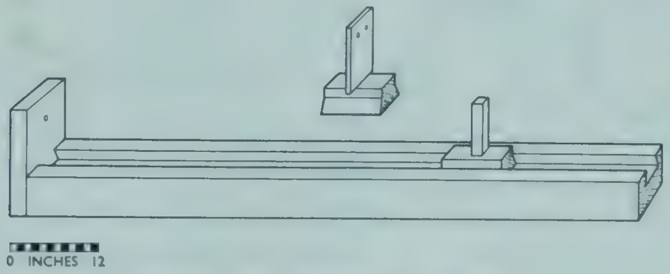

FIGURE 345—*The four-cubit dioptra.*

In principle this instrument is related to the primitive use of the index-finger or palm held at arm's length as a means of approximate measurement of angles (finger-breadth = 1½°; palm-breadth = 6°). The same principle occurs later in the invention of the cross-staff (or Jacob's staff, *baculus*) by Levi ben Gerson (1288–1344), and its revival by Regiomontanus and employment in navigation by Martin Behaim (p 528). In this later form the cross-staff consists of a set of cross-pieces of various lengths, any of which may be slid along a rod held with one end against the eye. Still later refinements include that due to Gemma Frisius (1508–55), where a single cross-piece is fitted with a scale and a pair of sliding sights so that measurements can be taken asymmetrically.

(f) *The armillary* astrolabon *and associated devices.* The armillary *astrolabon* is the most complex of Ptolemy's instruments, and is also the one that has caused most confusion; through its name it has often been confused with the quite different plane astrolabe (Theon calls the latter the 'little astrolabe'), and through its appearance it has been confused with the armillary sphere, a later device used primarily for teaching and demonstration rather than for observation. Also, as the 'armillary astrolabe', it has been confused with the spherical astrolabe, a calculating instrument described by the Alfonsine astronomers.

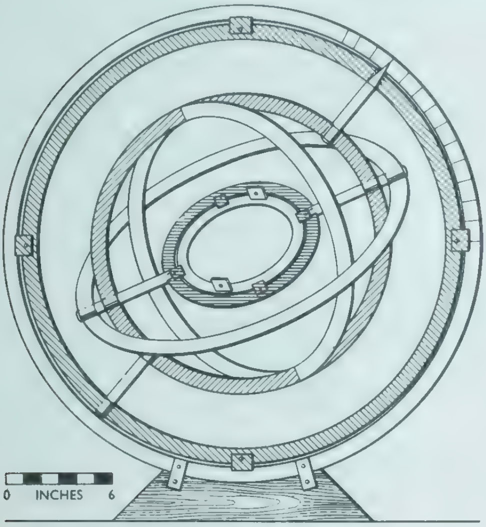

FIGURE 346—*The armillary* astrolabon.

The instrument described in the *Almagest* consists of a nest of seven concentric bronze rings, the innermost of which carries a pair of sights in the same fashion as the meridional armillary (figure 346). The whole device may have been mounted on a pillar and set in the meridional plane, but Pappus's words suggest that it was suspended in some way. The purpose of the many rings is that, once the inner sights have been set on the Moon or a fixed star, the ecliptic co-ordinates (latitude and longitude) may be read directly without the extended calculations needed to derive this information from altitudes and azimuths. This is of the greatest importance, since the kernel of Ptolemaic theory is its treatment of planetary motion in which the ecliptic is the prime plane of reference. The three outer rings merely provide a framework which enables the fourth ring to rotate in the plane of the equator and to follow its diurnal rotation. The framework also carries an axle arranged at the proper inclination to follow the motion of the axis of the ecliptic, and this axle carries near the centre a pair of sights that may be used to determine the latitude from the ecliptic of any star or of the Moon. An extra ring is supplied on the outer portions of the ecliptic axle so that the instrument may be used to make simultaneous observations of two celestial bodies. With so many moving parts, the armillary *astrolabon* would have been subject to considerable error if not constructed with extraordinary skill; nevertheless, it was probably with this type of device that Ptolemy and perhaps Hipparchus took most of the observations for their famous star catalogues.

The need for making observations directly in ecliptic co-ordinates—or, at the worst, of having a geometrical device to transform altitude and azimuth into this form convenient to theory—was very real during the Middle Ages, when trigonometrical computation was a long and tedious process. An ingenious alternative to the armillary *astrolabon* introduced in the thirteenth century, the 'torquetum' or 'turketum' (figure 347), consists of a set of inclined, rotating tables, the lower one being set on a desk-like stand so that it may be slanted according to the latitude of the place of observation and set in the plane of the meridian. On this is pivoted another table representing the plane of the ecliptic, set at an angle of 23½° to the first. This carries a theodolite-style pair of graduated circles with a sighting-alidade. The usefulness of the instrument is much enhanced by the addition of a semicircular protractor (*semissis*) and plumb-bob to the alidade; this enables observations and calculations of altitudes to be readily performed.

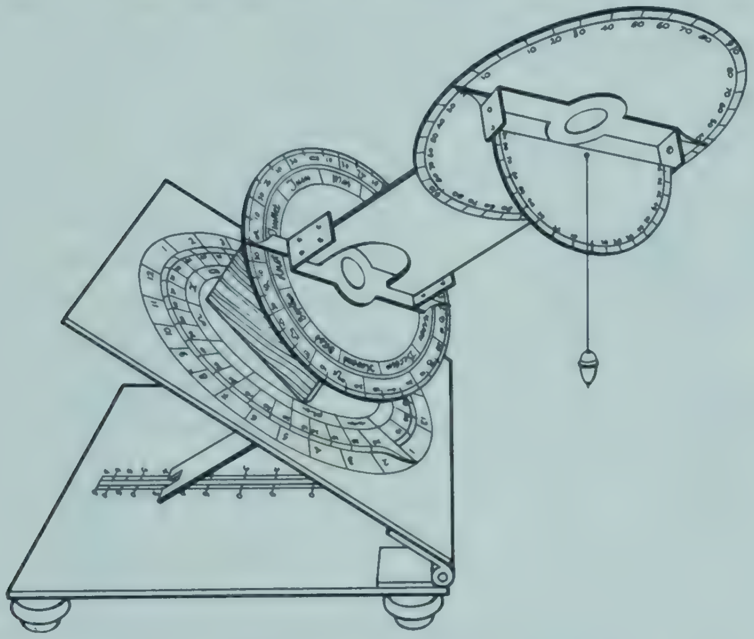

FIGURE 347—*The torquetum.*

The *rectangulus* (figure 348), a skeleton version of the torquetum, was invented by Richard of Wallingford, chief of the Merton astronomers, in 1326. It avoids the use of the many divided circles of the parent instrument, but it must have been awkward to use and does not seem to have had any lasting vogue.

(g) *The sighting-tubes.* The modern scholar is so accustomed to seeing an astronomer depicted with his telescope that it has sometimes escaped attention that a number of medieval manuscript miniatures show the astronomer apparently gazing through a long tube held on a stand or by his hands. Such pictures must give rise to the suspicion that the instrument in question is actually some sort of telescope with lenses, and although the evidence is weak, it cannot be summarily discarded merely because of the great improbability of the invention having been made so early.

There appear to be two groups of pictures, in one of which the tube is mounted on a stand, while in the other it is trumpet-shaped and held to the eye. The first type occurs in conjunction with a text by Gerbert (Pope Sylvester II, 999–1003) in a St-Gall manuscript of 982. The instrument (figure 349 A) is designed as an aid to observing the celestial pole; it is directed towards the pole star by a teacher, and his students may then look through and learn without error which star it is. The second group of illuminations (figure 349 B) is more puzzling, since an unmounted tube can hardly be used for such a purpose. Unfortunately no text has been discovered which describes such an instrument as is depicted, and even in the illuminations the tube is sometimes replaced by a magic wand suitable for the astronomer-sorcerer. Perhaps the tube served as a funnel for concentrating the rays of light from the stars—a notion quite in keeping with Aristotelian optical concepts.

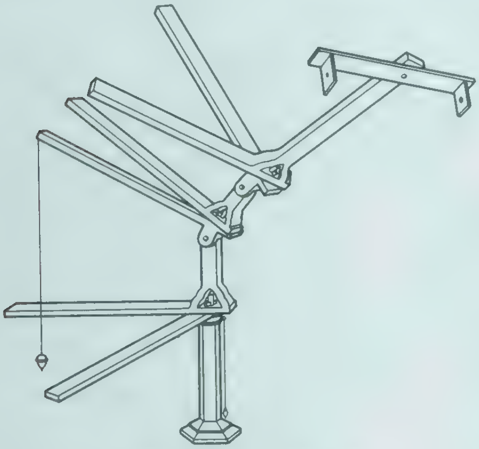

FIGURE 348—*The* rectangulus.

IV. PORTABLE SUN-DIALS

The common, fixed sun-dial is a device of great antiquity. It is no great step from marking the shadow of some convenient building, pillar, or natural object to the construction of a vertical or horizontal slab with its own little gnomon for casting a shadow of convenient size. Even during the early Middle Ages many Saxon scratch-dials were constructed on church walls. The more primitive of these devices can hardly qualify as precision instruments, but one special form of masonry dial known from classical times as the *skaphe* or hemicycle was sufficiently accurate for all daily purposes and even for the timing of eclipses. Many examples of the instrument have been preserved (figure 350).

More important technically are the numerous and often very ingenious portable sun-dials. Their small size demanded a certain accuracy in construction, and their portability led to problems that do not arise with an instrument rigidly fixed with respect to the meridian and horizontal planes.

(a) *Altitude-dials.* The shadow of a fixed object changes throughout the day both in direction and in length, and either of these variations or any combination of them may be used for the measurement of time. When a portable form of sun-dial is required it is perhaps natural to single out the length-variation, because it need involve no determination of the direction of the meridian and the instrument will not therefore require to be orientated before use. Because of its simplicity, the measurement of shadow-lengths is probably as ancient as any other means of telling the time, and the primitive empirical method of estimating in paces the length of a man's own shadow seems to be as ancient as it is widespread. Shadow-lengths vary not only throughout the day but from month to month through the cycle of the year; they are also dependent on the latitude of the place of observation. It follows that tables or graduations must be available for various times during the year, and that these data are valid only for the latitude of the intended place of use. Typical of such tables is one given by Bede (673–735), which shows the length of the shadow of a 6-ft gnomon at noon, 9 a.m., and 3 p.m. at intervals of about a fortnight throughout the year; it is constructed for a latitude of about 55°, corresponding to the position of his monastery at Jarrow.

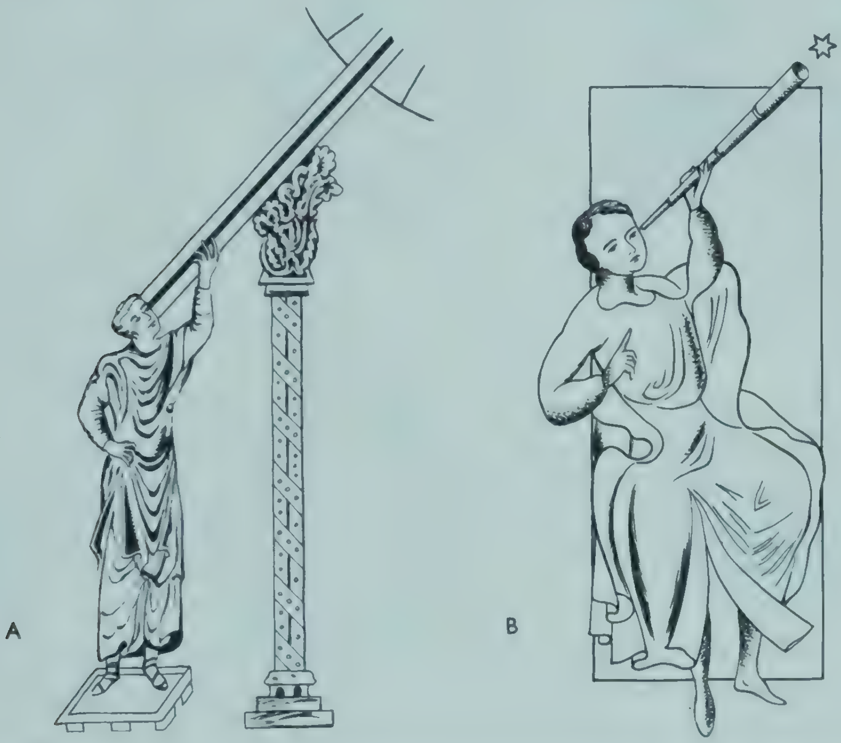

FIGURE 349—(A) *Gerbert's sighting-tube. From a St-Gall manuscript, now lost;* (B) *similar tube used without a stand, from a thirteenth-century manuscript.*

The earliest form of instrument for such measurements seems to have been the Egyptian shadow-clock (tenth to eighth centuries B.C.), and very similar devices are still in use in that country The shadow-clock is nothing more than a horizontal graduated rod, with a vertical projection of some sort used as the gnomon (vol I, figures 44–45). The graduations of the rod seem to have been arrived at empirically, and the annual variation must also have been allowed for by rule of thumb. A later type of Egyptian altitude-dial (probably of the Roman period) illustrates a fundamental improvement in the technique of the instrument. It consists (figure 351 A) of a small wedge with a rectangular block set before it. In use, the device is orientated so that the shadow of the block falls squarely on the slanting face, and the length of the shadow may be then read on one of the scales marked lengthwise on this face. Scales are provided for each month of the year, but since the variation is cyclical one scale may be made to serve for two months equidistant from an equinox.

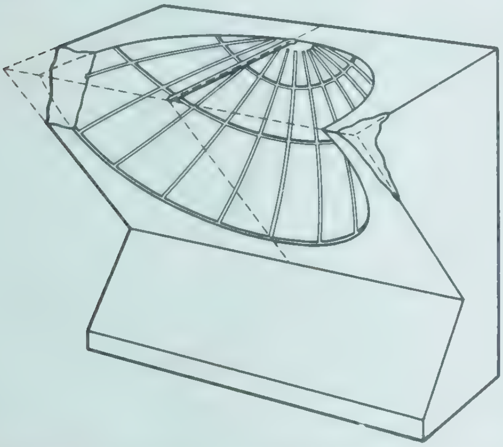

FIGURE 350—Skaphe, *or hemicycle sun-dial, found at Civita Lavinia.*

A Roman 'ham' dial from Herculaneum (figure 351 B) shows a marked improvement on the Egyptian forms, in that it consists of a flat plate which may be suspended from a ring so that it automatically takes up a vertical position and does not need to be levelled by independent means. In the 'ham' dial the gnomon protrudes from the surface of the plate, which is orientated until the tip of the shadow falls on the graduations of the appropriate column containing divisions for the month of the year.

In practice it is found that the use of a single fixed gnomon leads to inconvenience in graduating the instrument, and this difficulty is removed in the design of the earliest English instrument, a Saxon (ninth or tenth century) dial of exquisite workmanship found at Canterbury Cathedral in 1939 (figure 351 C). A strikingly similar example, this time of Muslim origin, is a dial made in 1159–60 for the Sultan Nūr al-Dīn (figure 351 D). In both dials the gnomon is detachable and may be placed in a socket above any of the appropriate month-columns. Each separate hour of the day is marked on the Muslim instrument, but the Anglo-Saxon dial agrees with Bede in distinguishing only the 'tides' at noon, 9 a.m., and 3 p.m.

The cyclical character of the annual variation is probably responsible for the appearance of dials in the form of a cylinder with the columns for each month arranged around it (figure 351 E). This type of instrument, mentioned by Chaucer as the 'chilindre', and still in daily use in the Pyrenees as the shepherd's dial,

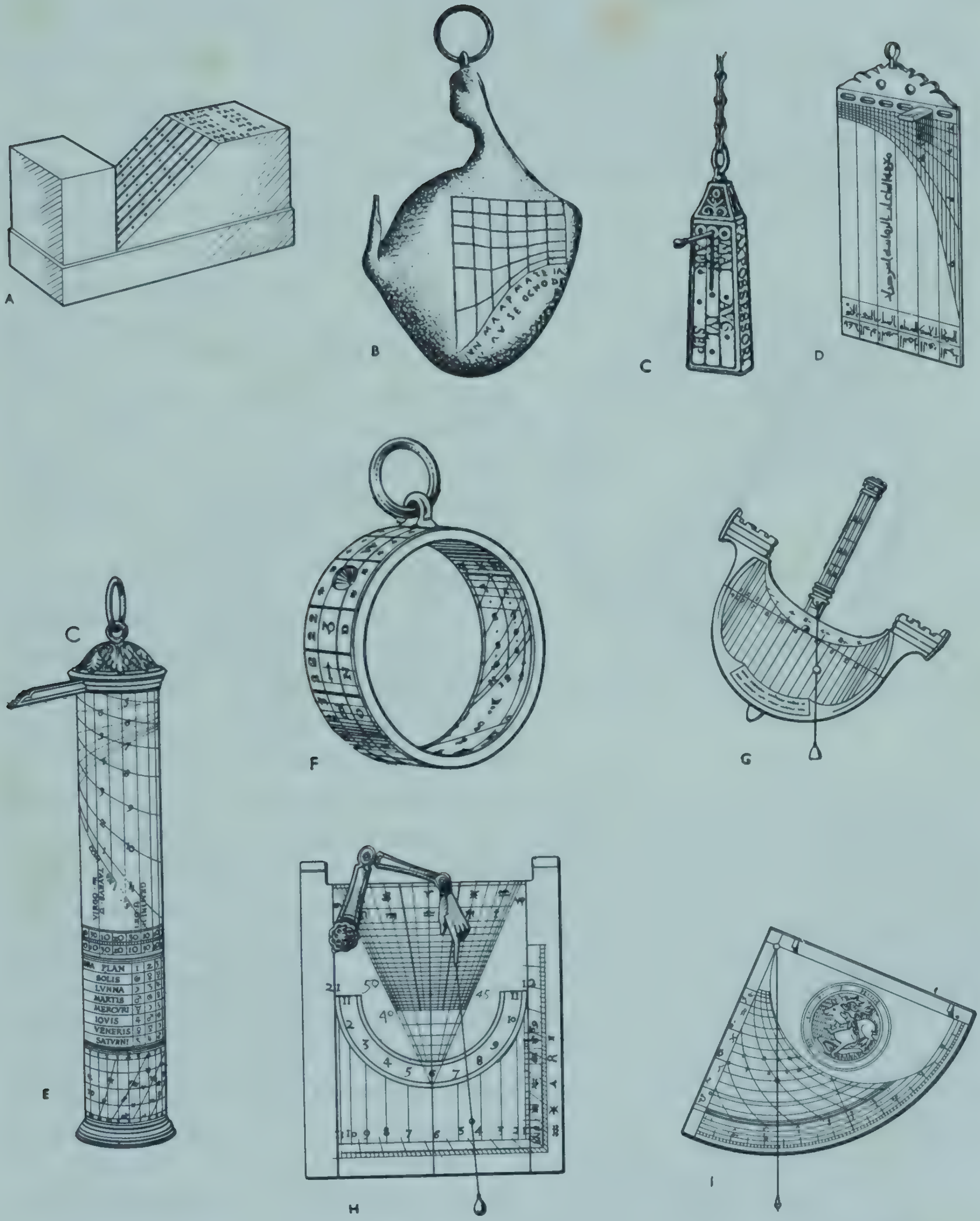

FIGURE 351—*Sun-dials of various types and periods.* (A) *Egyptian wedge-dial;* (B) *Roman 'ham' dial* (C) *Saxon dial from Canterbury;* (D) *Islamic dial of similar type;* (E) *'chilindre' or shepherd's dial;* (F) *ring-dial;* (G) *navicula or ship-dial;* (H) *universal rectilinear dial;* (I) *horary quadrant (dated 1399).*

is the subject of manuscript texts dating from the fourteenth century; the earliest extant example, dated 1455, is in the National Museum at Munich.

Another type of common altitude-dial, probably not so old as the 'chilindre', is the poke (pocket) dial or ring dial.[1] Instead of a gnomon, the poke dial has a hole which casts a spot of light on a scale in the interior of a small squat cylinder like a napkin ring (figure 351 F). Sometimes there are scales for the various months of the year, but in later improved versions the hole is made in a slider which can be adjusted to give approximate compensation for the annual variation in the Sun's meridian altitude. Neither this nor any of the preceding types of portable dial could be expected to tell the time more accurately than within about half an hour. Since such dials were frequently used in latitudes other than that intended, the accuracy must often have been even less.

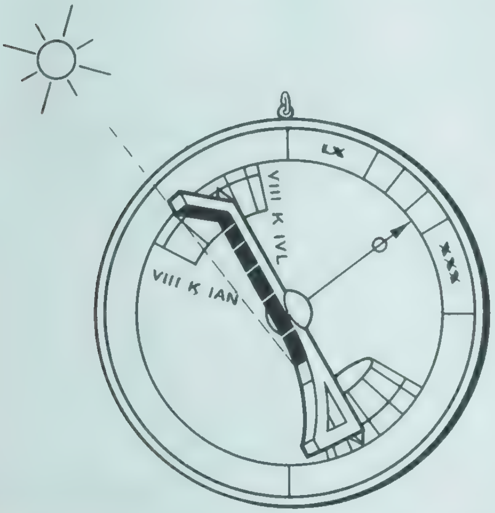

FIGURE 352—*Roman equatorial dial, c* A.D. *250–300.*

It is possible, by ingenious geometrical construction, to design an altitude-dial adjustable for any latitude of observation. The earliest design of this type is the *navicula de Venetiis* (little ship of Venice), first described in fourteenth-century manuscripts (figure 351 G). It takes its name from its shape; the curved semicircular plate resembles the outline of a ship, a central pillar containing a latitude-scale passes for a mast, and two projections for pinnules resemble fore- and after-castles. A similar type of dial was designed by Regiomontanus and is known as his universal rectilinear dial (figure 351 H); the 'mast' is replaced by a jointed pointer, which carries the plummet. In use both instruments are held in the vertical plane and tilted until the shadow cast by one pinnule falls on the other. The point of suspension of the plumb-line, and the position of a marker-bead along it, are adjusted by scales corresponding to latitude and to time of year, and the hour is read on one of a series of lines over which the bead can range.

The portable quadrant is included in this section because although it was used as a more general astronomical instrument, and adapted for terrestrial surveying and as a variation on the astrolabe, it is as an altitude sun-dial that it probably had its greatest vogue. The instrument (figure 351 1) consists of a quadrant of metal or wood, furnished with a pair of pinnule-sights along one of its terminating radii and fitted with a plumb-bob suspended from the centre of its arc. The fundamental idea of the economy of using a quadrant instead of the larger and heavier full circle is apparent already in Ptolemy's plinth (p 587), but whether the portable form of instrument was introduced by the Alexandrians or by the Muslims who succeeded them remains uncertain. The earliest known portable quadrant seems to have contained a shadow-square for surveying (p 528) as well as the divided arc; it is in this form that it receives its first European mention by Leonardo da Pisa about 1220. Soon afterwards Profatius (Jacob ben Tibbon, a Jewish astronomer of Montpellier) mentions the 'old quadrant' (*quadrans vetus*) as containing the divided circle, shadow-square, and a set of horary lines, in contradistinction to his 'new quadrant' (1288, revised 1301) which included an astrolabe projection as well. From the fourteenth century onwards there is a

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[1] The latter term is to be deprecated as ambiguous; there are 'universal' ring dials, finger-ring dials, and others.

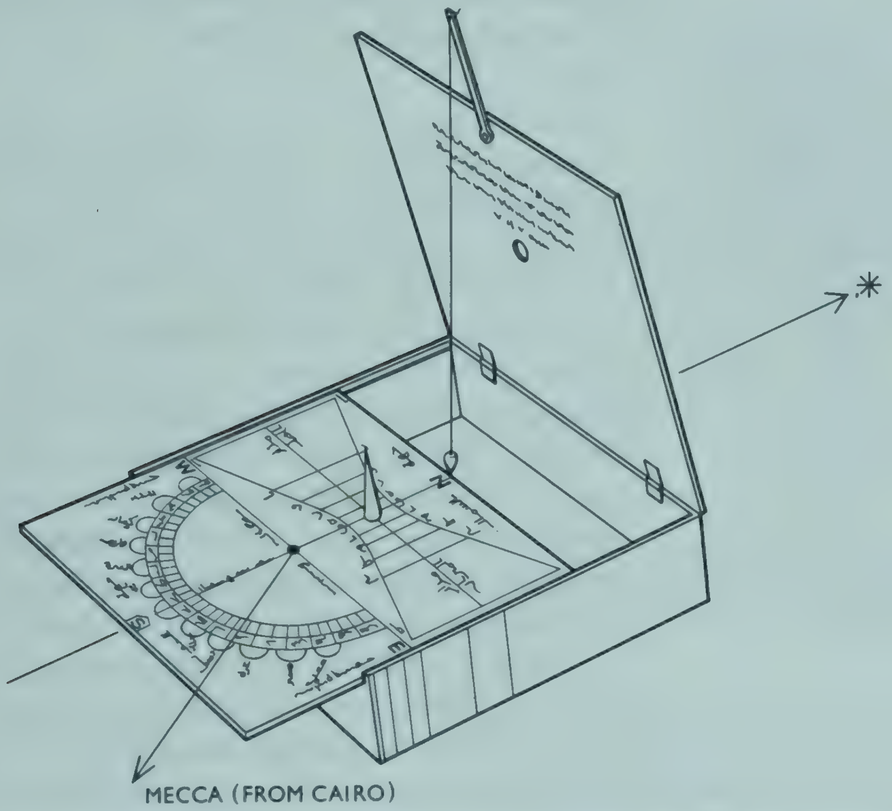

FIGURE 353—*Syrian double-dial, which could be used to determine the* qibla (*direction of Mecca*). *Fourteenth century.*

considerable literature on the portable quadrant in its European and Muslim, and old and new, forms. Its economy of size for a given radius of arc, and the scope for ingenuity in devising suitable scales and graduations for various purposes, made it a favourite subject amongst the inventors and engravers of scientific instruments, and the ease with which it could be constructed accounts for its widespread employment for angle measurement.

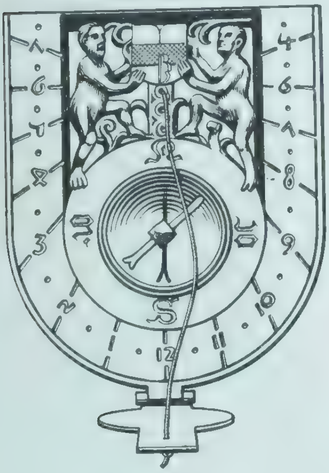
FIGURE 354—*An early German horizontal dial fitted with a compass. It is dated 1453, but may be a later copy.*

(b) *Direction-dials.* As has been pointed out, a sun-dial can measure time by using the direction of a shadow instead of its length. This is not so convenient if the dial is a portable one, because some means must then be found for orientating the instrument along the plane of the meridian. Before the invention of the magnetic compass this was very difficult, and examples of such dials are consequently very rare. The only known European example (figure 352) is a Roman dial (A.D. 250–300) which solves the problem by arranging a 'mural quadrant' in a plane parallel to the plane of apparent rotation of the Sun at a given time of the year and at a given latitude of observation. This is effected by rotating the quadrant on an inner disk so that it is set at the declination of the Sun in the ecliptic, and then setting the inner disk on an outer disk at an angle corresponding to the latitude of the place of observation. The whole device is next supported in the vertical plane by means of a ring, and twisted until the shadow of the gnomon falls along the arc of the quadrant and indicates the time. An inverted use of such direction-dials is found in Islam; a fourteenth-century dial from Aleppo (figure 353) uses an altitude-dial to find the time and then sets a direction-dial along the meridian by turning it until it reads correctly. The double dial thus acts as a sort of sun-compass and can be used to determine the direction (*qibla*) of Mecca, which Muslims need to know for ritual purposes. To facilitate this operation, the Aleppo dial and others of similar construction are furnished with a special scale showing the direction of Mecca from various cities.

The introduction of the magnetic compass led to the devising of many types of direction-dial orientated by this means. Ships' inventories record 'dyolls' from 1410–12, and *horloges de mer* appear at about the same date, but these are probably sun-dials (without compasses) and sand-glasses. The earliest known compass dials are several of almost identical construction dated 1541–63, in which the shadow is thrown by a style of thread stretched between the base-plate and a vertical pillar which can fold down for ease of carrying (figure 354). The style is set, according to latitude, so that it is parallel to the polar axis. An interesting feature of these dials is that the compass-plate is marked with a line showing the deviation of magnetic from true north. This practice was followed by later instrument-makers, but the deviation recorded is often traditional rather than actual.

V. WATER-CLOCKS

The oldest time-measuring devices independent of astronomical phenomena undoubtedly indicated merely the passage of arbitrarily fixed periods, as does the modern egg-timer. The sand-glass is not known by explicit mention until the second half of the fourteenth century, but its precursor the clepsydra, which used water instead of sand, was known in Egypt about 1400 B.C. and is probably of much greater antiquity. One found at Karnak, and believed to date from the reign of Amenhotep III (*c* 1415–*c* 1380 B.C.). consists of an alabaster bowl with a small hole near the bottom through which water was allowed to leak away. Some extant clepsydra jars from Egypt have scales marked on the inside, but for these to measure equal intervals of time the graduation would have to be made empirically and the water-level at the start would have to be at exactly the right height on the scale (vol I, figure 48).

(a) *The constant-flow clepsydra.* The first technical problem of the water-clock is to make the water flow at a uniform rate. This cannot be done readily with a simple leaking jar, although the sloping sides of the Egyptian clepsydras help to compensate for the decreasing head of water. The most important step in the design of the true water-clock was made by Ctesibius (? *c* 100 B.C.). Vitruvius tells us that he was the first to fashion the leak-hole in a gem or in gold so that it should not get worn away or clogged by corrosion. He also inverted the usual practice by measuring the water flowing out of the jar instead of that which had been poured in or which remained, and, most important of all, he arranged for a continuous flow of water into the jar and an overflow-pipe near the top so that the leak always occurred under a constant head of water. The water was allowed to drip into a cylindrical container, and in the simplest form its height could be read by means of a time-scale on the inner wall. Ctesibius, being of an inventive and mechanical turn of mind, preferred more elaborate devices (figure 355 A) and fitted the cylinder with a float moving a rack and pinion; this provided motive power for working little devices (*parerga*) and making signals to be seen or heard at the end of each hour.

(b) *The parastatic clock.* The next stage was to fit the float with a pointer that could travel along a vertical scale marked in hours. This was not so simple as it sounds, for the hours that it was desired to indicate were not the equal hours of astronomy; they were the unequal hours of which there were always just twelve from sunrise to sunset, regardless of the length of the day (p 565; vol I, p 113). Ctesibius tried at first to adjust the clock by adding a valve to the leak-hole, but this proved too erratic in action. As an alternative, a number of scales varying in length from month to month were inscribed on a pillar (*parastatica*) along which the pointer (in the shape of a manikin) could travel. By making the hour-marks into a set of continuous sloping lines around the cylinder (figure 355 B) the scale could be accurately turned to the appropriate length for any day of the year.

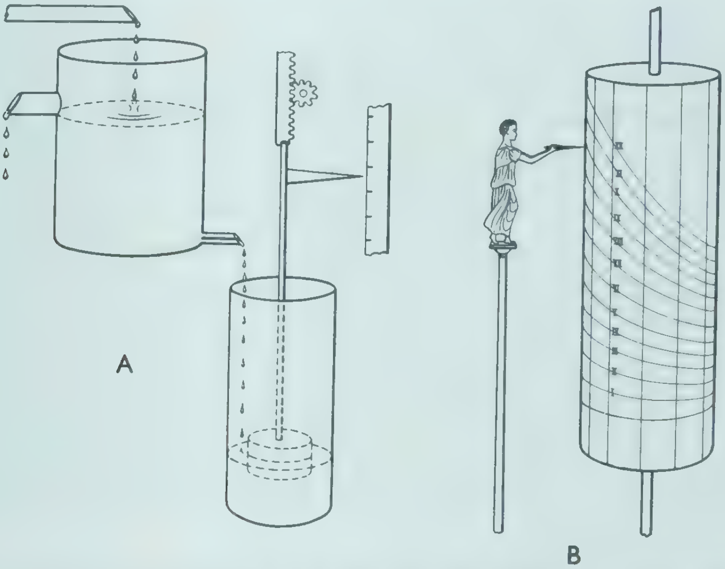

FIGURE 355—(A) *Constant-head clepsydra with float operating pointer on time-scale and (through the rack and pinion) automata;* (B) *parastatic water-clock.*

(c) *The zodiac-regulated clock.* Vitruvius gives an account of an ingenious solution to the difficulty experienced by Ctesibius in adjusting the outflow of the parastatic clock so that a single scale might be used throughout the seasons. The device functions by varying the depth of the hole below the water-level rather than by altering the size of the hole or adding a valve. The hole of the clepsydra is placed near the circumference of a bronze disk which can be turned in its setting, and a pointer is fixed on the disk near to the hole (figure 356). This pointer indicates a position on a circular scale marked with the signs of the zodiac and evenly graduated in 365 days. When the Sun is at the summer solstice in Cancer the hole is uppermost and the rate of outflow is small, so that the cylinder fills slowly; at the winter solstice the pointer is in Capricorn and, the hole being lowermost, the rate of flow is greatest and the cylinder fills more rapidly in the shorter day. The construction is in fact only an approximation for other days of the year, but the disk could always be turned slightly to correct empirically for any inadequacy of the time-keeping.

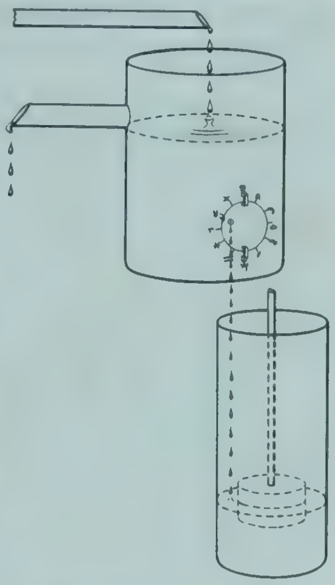

FIGURE 356 — *Zodiac-regulated water-clock, the height of the hole adjusting the flow according to the length of the day.*

VI. THE ASTROLABE

The name astrolabe (Greek *astrolabon*, star-taker) has been applied, at some time or other, to almost every astronomical instrument except the telescope. The confusion with Ptolemy's armillary *astrolabon* has already been noted (p 591) and this, together with a well known but altogether misleading letter from Synesius (*c* A.D. 410) to Paeonius, has led to the ascription of the plane astrolabe to Ptolemy and even to Hipparchus. It is a perfect instance of a correct conclusion being drawn from false evidence, for although the earliest extant text on the plane astrolabe is that of Philoponus (*c* A.D. 530) it has now been conclusively demonstrated by Neugebauer that the instrument was known to Ptolemy, and that the underlying theory of stereographic projection was indeed probably known in the time of Hipparchus.

(a) *Principle of stereographic projection.* Stereographic projection is one of many devices that may be used to map the surface of a sphere on to a flat plane; it has the special property of mapping all circles on the sphere as circles on the plane, and of projecting angles between two lines on the sphere into equal angles between two lines on the plane. For the purpose of the ordinary plane astrolabe, the map is made by projecting from the south pole of the celestial sphere on to a plane perpendicular to the polar axis (figure 357). If one held a sheet of paper directly over the north pole of a transparent globe and looked up from the south pole of the globe towards the paper, the mapping could be performed visually.

A full account of the construction and use of this projection is given by Ptolemy in one of his minor works, the *Planispherium*; but he is clearly making use of earlier material, for Hipparchus was able to solve problems on the sphere without a knowledge of spherical trigonometry, and it is therefore very reasonable to presume that his method was that of stereographic projection. Once the idea of stereographic projection is familiar, it can be only a very short step to the basic principle of plane astrolabic devices. For these, two plates are constructed, one representing the celestial sphere and engraved with the position of stars and the ecliptic in which the Sun moves, and a second representing the visible horizon, zenith, lines of constant altitude, and lines of constant azimuth visible to an observer at the particular latitude at which the instrument is to be used. These two plates are then placed one over the other, and are pivoted together at the north celestial pole in both cases. By rotating one plate with respect to the second the diurnal rotation of the celestial sphere can then be simulated, and many types of calculations may be thus facilitated.

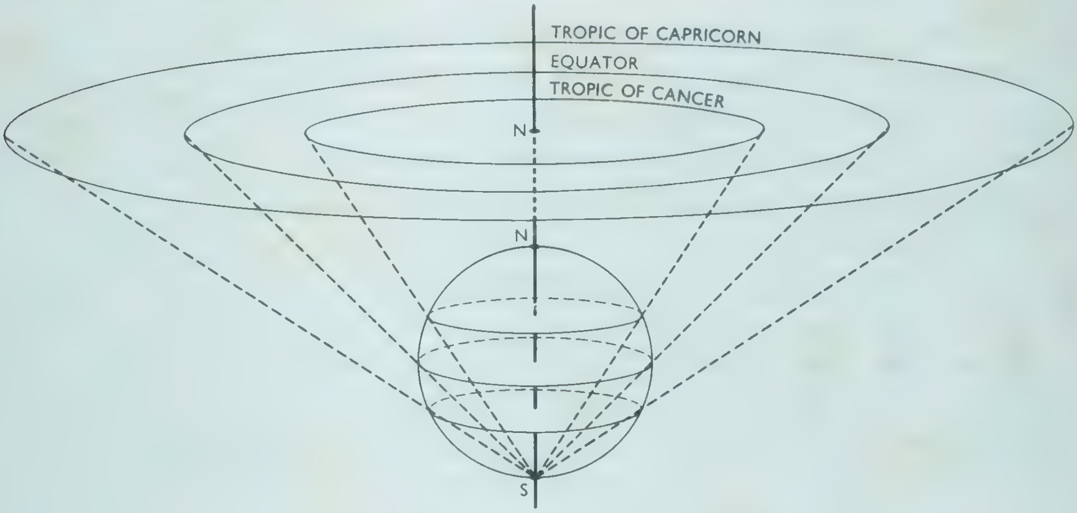

FIGURE 357—*Principle of the stereographic projection.*

(b) *The anaphoric clock.* It seems very likely that the first application of the principle just described was in the construction of a star-map made to rotate so that it showed artificially the diurnal rotation of the heavens. This was not only effective as an ingenious spectacle, but could also be of practical use in showing the rising and setting of the Sun and the progress of the customary 'unequal hours' between these limits. The difficulty of recording unequal hours with a water-clock of constant flow has already been mentioned (p 602). The anaphoric clock, as described by Vitruvius, is simply a constant-flow clepsydra arranged so that the rising float is connected to a sand-bag counterpoise by means of a flexible bronze chain, which passes round an axle and turns it through one revolution in a solar day. The axle carries a large circular star-map, laid out by stereographic projection (figure 358), and in front of this map is placed a stationary grill corresponding to the projection of the horizon and visible hemisphere for the desired latitude (Vitruvius chooses Alexandria, *c* 31° N). Part of a star-plate from an anaphoric clock dating from the first or second century A.D. has been found at Salzburg; it contains delineations of some constellations, and also part of a circle which originally contained 182 or 183 holes. A little disk representing the Sun was probably plugged into the appropriate hole and moved to the next one every second day, so that it made one complete rotation in the plate during a year.

(c) *Evolution of the plane astrolabe.* The greatest technical difficulty of the anaphoric clock lay in the construction of the grill. If only a few wires were used, the device was too inaccurate; with many thinner wires the grill became fragile and liable to deformation and tended to obscure the underlying star-map. We do not know who made the brilliant suggestion that the grill might be engraved on a solid plate and a 'transparent' star-map rotated above it (figure 358). The important point is, of course, the conception of a transparent disk and its realization by cutting away everything from the star-map except the indispensable circles and a small number of pointers marking the position of only the brightest stars. This improvement transformed the instrument from the realms of demonstration and crude time-indication to the greatest heights of utility, as a calculating device suitable for working with sufficient precision most of the problems of spherical astronomy.

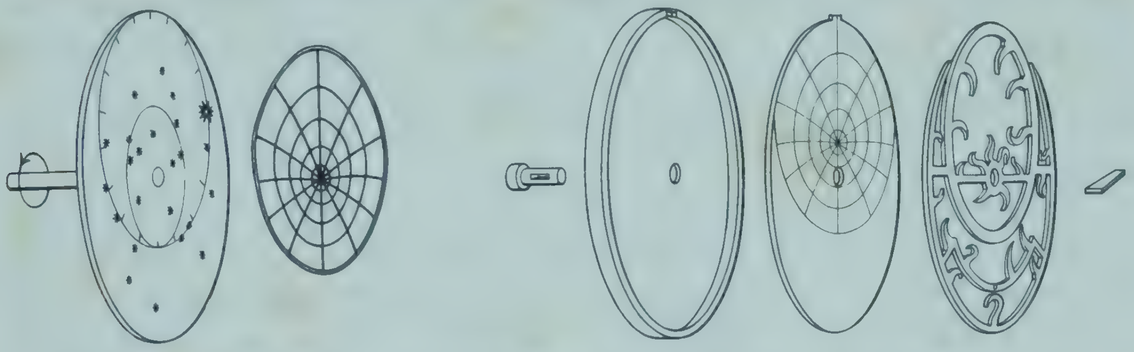

FIGURE 358—(Left) *Rotating star-map and fixed grill of anaphoric clock (reconstructed)*; (right) mater, *plate, and star-map (rete) of an astrolabe, showing the same arrangement reversed.*

In the *Planispherium* Ptolemy seems to refer to a 'horoscopic instrument' which has the fixed stars marked on the *aranea* or spider. Unfortunately we have no other evidence to support an assertion that this instrument is a true astrolabe, and it is therefore necessary to fall back on the evidence of the earliest available texts on the instrument. In date, the first is a treatise by Philoponus (*c* A.D. 530), but it has now been shown that this is merely a later edited version of a treatise by Theon of Alexandria (*c* A.D. 375) which is preserved with only slight changes in a text by Severus Sēbōkht (before A.D. 660). A useful indication of the evolution of the instrument is the history of its name. For Ptolemy and Proclus, *astrolabon* is always the armillary *astrolabon*. Theon distinguishes the plane instrument as the 'little astrolabe' (p 591); and Philoponus calls it simply the 'astrolabe', in common with all medieval writers on the subject.

An interesting aspect of the early history of the plane astrolabe concerns the circular outer limit of the instrument. In Ptolemy's *Planispherium*, the letter of Synesius, and perhaps also the treatise of Sēbōkht, the outer border represents the Antarctic circle of the celestial sphere—the southernmost limit of stars that are visible from the inhabitable portions of the world. In all later texts and all extant instruments (tenth century onwards) the outer limit is the Tropic of Capricorn, and the instrument cannot therefore always show the position of stars lying south of this tropic and visible to an observer in the northern temperate zone of the Earth.

(d) *Construction of the plane astrolabe.* The basic design of the instrument shows no change from the earliest known examples of the tenth century to the obsolescent productions of the seventeenth and even eighteenth centuries. Only in the techniques of metal-work and decoration has the appearance of the astrolabe altered.

The body of the instrument (figure 359) consists of the *mater*, a thick plate of metal with a circular depression hollowed out of the obverse to contain a set of thin circular tablets engraved with lines of altitude and azimuth for a series of convenient fixed latitudes. Usually the tablets are keyed by a notch and tag so that they will fit in the *mater* only when correctly positioned. At one point of its circumference the *mater* bears a lug or 'throne', to which are attached a swivel and a suspensory ring to hold the instrument; its weight then aligns the *mater* in a vertical plane. Above the tablets, in front of the face of the *mater*, is an open-work metal plate, the rete, containing a set of pointers indicating the positions of the fixed stars, and a circle representing the zodiac.

The whole instrument is fastened together by a removable peg running through the centre of the *mater*, tablets, and rete. It frequently carries also a small pivoted rule on the face of the instrument, and a rule fitted with a pair of pinnule-sights (the alidade) on the dorsum of the astrolabe. In later instruments the peg consists of a screw and nut, but in all the early versions the peg is fixed by a little wedge (the 'horse') which passes through its end.

The majority of astrolabes are made of brass because of the ease with which it can be obtained in good plates and satisfactorily engraved with fine lines.

Sometimes the *mater* is cast in brass or in bronze, but more often it is hollowed out of a thick sheet; sometimes it is built up from a thin plate on which a heavier rim has been riveted or brazed. From the sixteenth century onwards cheap astrolabes, and indeed many other types of instrument, were made by pasting printed diagrams on suitably cut sheets of wood. Islamic astrolabes are sometimes found embellished with precious stones and highly ornate decorative engravings; their retes often contain zoomorphic star-pointers and are of great intrinsic beauty.

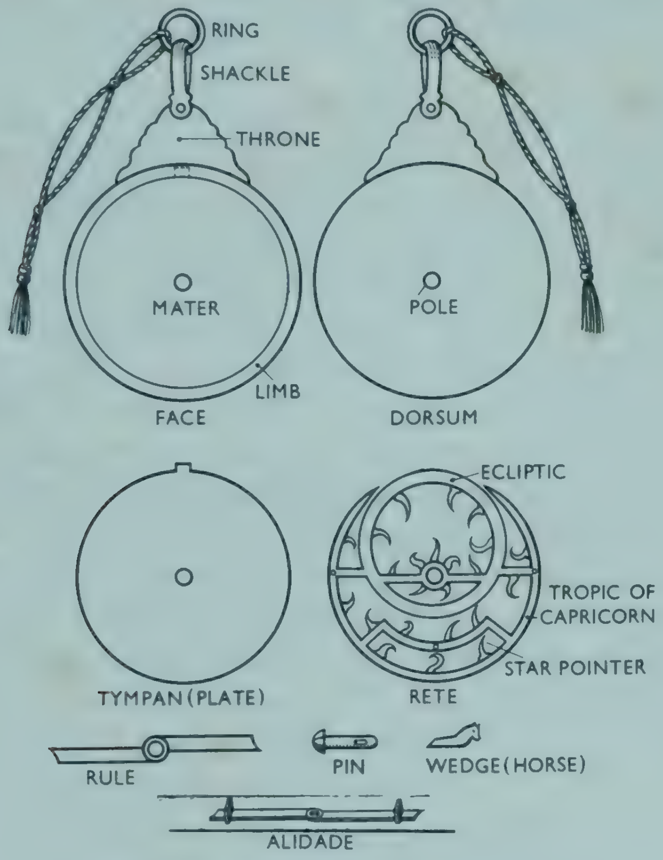

FIGURE 359—*The component parts of an astrolabe.*

(e) *The dorsum of the astrolabe.* Essentially the astrolabe is a calculating instrument, but it seems to have been adapted at an early stage in such a way that it could also be used for observing the altitude of the Sun or fixed stars. From such an observation, and using the face of the instrument, one may calculate such things as the time of day or night and the sign of the zodiac which is in the ascendant. This adaptation as an instrument of observation is secondary, in almost the same way as a modern slide-rule may also carry a scale of inches or centimetres. It is most probable that the original form of the device had no sighting-alidade, which was later added so as to take advantage of the divided circle of the instrument. Before the invention of the dividing-engine it was laborious and costly to produce an accurately divided circle by a process of continued bisection of angles and laying off calculated chords. Even the earliest treatises of Philoponus and Sēbōkht refer to the alidade on the dorsum of the instrument, so it is evident that the astrolabe had been thus improved at some very early stage.

At first the dorsum was marked only with a circular arc containing degrees and their subdivisions. The first Muslim astronomers improved upon this by adding many devices for geometrical computation, including a 'shadow-square'; this showed the variation in length of a vertical or a horizontal shadow of a fixed stick—in effect the scale (figure 329) gives the tangent or cotangent of the angle observed. The shadow-square made it possible to use the astrolabe also as an observing-instrument for terrestrial use. One could measure the shadow of a tower or sight its topmost point and deduce its height by means of the device. Such examples are frequently quoted in texts, but the method probably served more as an ingenious application used by teachers of mathematics to show that geometry was a 'practical' subject than as a means commonly employed by any surveyor, builder, or military engineer before the Renaissance. The shadow-square was sometimes included on quadrants, and was even transformed into a separate instrument, the geometric square, which consisted of an open square frame with an alidade or a plumb-bob pivoted at one corner. The portable quadrant with a shadow-square was known to the Muslims from the time of Al-Khwārizmī (*c* 840) and was introduced into Europe by Leonardo da Pisa (*c* 1220). The geometric square was also known to the Muslims, but although it was introduced into Europe by Gerbert (940?–1003) it did not become popular until the development of practical trigonometrical methods of indirect measurement by Purbach (*c* 1450) and the rise of instrumental surveying in the sixteenth century.

The *mariner's astrolabe* can hardly be called an astrolabe at all; it consists only of the alidade and divided circle that compose the observing portion, the whole of the calculating apparatus being omitted. The instrument is made heavier than usual, and as much as possible of the inside of the outer limb is cut away, so that the device may hang in a vertical plane and be little disturbed by wind. As an instrument for taking the height of the Sun or pole star, to derive the latitude, it seems to have been invented about 1535; some earlier mentions probably refer to the use of astronomical astrolabes at sea. After 1600 its popularity declined, as better alternative instruments became available.

(f) *Later history of the astrolabe.* The astrolabe attained widespread use in Islam very soon after its introduction there. The first writer on the subject is reputed to be Al-Fazārī (*c* 800), but his work remains unknown. It was perhaps displaced by that of his contemporary Mesahallah (Māshāllāh), a Jew probably of Egyptian descent. Mesahallah's treatise on the instrument became, in Latin translation, the most popular text on the subject in Europe during the later Middle Ages. Many other Arabic texts are known, and a number of ingenious variants on the astrolabe were evolved by the Muslim astronomers.

The earliest European text on the instrument is the *Sententiae astrolabii* (second half of tenth century), which has been attributed to Gerbert and describes the use but not the construction of the device. Full details of the geometric construction are first given in *De mensura astrolabii* by Hermannus Contractus ('the Lame'), abbot of Reichenau, about the middle of the eleventh century. It is probable, however, that the astrolable did not become common in Europe until the revival of astronomy towards the end of the twelfth century. The earliest extant Gothic instruments come from the second half of the thirteenth century and show great similarity in design and construction.

By the close of the fourteenth century the medieval astrolabe had achieved the peak of its popularity in Europe. Later there was a decline before the rise of the schools of instrument-makers in Germany and other countries. One of the most interesting of the later medieval texts is the 'Treatise on the Astrolabe' composed by Geoffrey Chaucer in 1391; it is one of the earliest technical works on science written in the English language, and is still one of the best and most lucid accounts of the astrolabe.

The revival of the astrolabe by the astronomers and instrument-makers of the Renaissance initiates the new age of craftsmanship and design in the construction of precision instruments. Although by this time the device was beginning to be outmoded by advances in astronomical theory and technique, its complexity and pleasing appearance made it the most popular subject for art metal-work, fine engraving, and the careful workmanship which later became so valuable when instrument-makers were able to turn their hands to the more varied experimental apparatus of the scientific revolution (ch 23).

VII. HERO'S DIOPTRA AND LEVELLING-INSTRUMENT

Hero's dioptra is a surveyor's instrument, a combined theodolite and water-level. It stands alone among devices known from antiquity, and is probably

Hero's own invention. It is described in his book *Dioptra*, in which there is a reference to a lunar eclipse that happened in A.D. 62.

The oldest manuscript of this work still extant, which is the source of all later ones, has lost eight pages; thus the description of the instrument is incomplete and has to be supplemented by conjectures and from deductions drawn from the description of its use. It must have had a foot, but whether this was a tripod or a sort of table we do not know. It must, however, have been possible to set the instrument strictly vertical, and a plummet was used for this purpose.

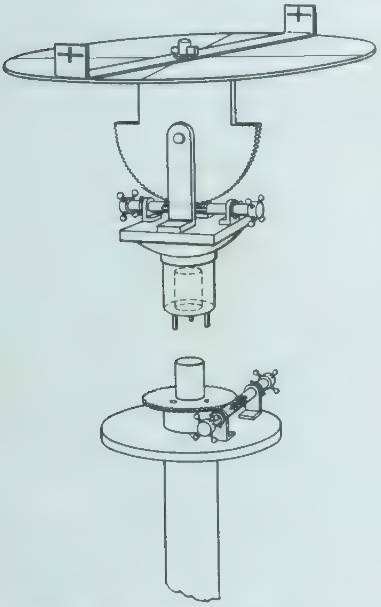

FIGURE 360—*Hero's dioptra (reconstructed diagram).* (Above) *The theodolite instrument;* (below) *the upper part of the base on which the theodolite and water-level rest.*

The instrument proper (figure 360) consisted of a column ending in a cylindrical axle, round the foot of which was a circular plate of bronze. A hub with a toothed wheel fitted the axle, and the wheel was engaged by an endless screw carried by uprights fixed on the bronze plate. This screw had a furrow as broad as the toothed wheel was thick, running lengthwise. When this furrow was opposite the toothed wheel the hub was free to turn in any direction; a turn of the screw would fix it and adjust it in any position.

On the upper side of the hub were three holes. The theodolite and water-level were each provided with a socket fitting the axle, and three pegs fitting the holes; in this way they were interchangeable. In the theodolite this cylinder ended in a Doric capital on which were two uprights; between them these carried a toothed semicircle of brass. An endless screw on the capital engaging with the teeth moved the semicircle and held it, just as the other screw did for the horizontal wheel. On the diameter of the semicircle was fitted a disk which carried the sighting-rod; it turned freely round an axle, and had two pointers moving over the surface of the disk. Here were engraved two lines at right-angles, one of them being in the plane of the semicircle. To use the dioptra for astronomical purposes the circle described by the pointers is divided into 360 degrees.

This is the theodolite; its principal use was to stake out lines at right-angles. By this means it was possible to stake out a straight line between two points not visible from each other, to find the distance to a remote point, or to direct a tunnel through a mountain. The theodolite could also be used in measuring the area of a piece of land, or for dividing it, even if it was inaccessible because of vegetation or buildings. By using the up-and-down movement of the sighting-rod it was possible to measure the height of an unapproachable point, such as the top of the enemy's wall, or the depth of a trench.

The water-level also had a cylinder with three pegs (figure 361); on its head were two small uprights to hold a wooden rod some 6 ft long. Into this rod was fitted a tube with upturned ends, to which vertical glass tubes were attached. When water was poured into this system, the water in the two glass tubes would stand at the same level. However, the surface of the water would not serve for sighting. Round each glass tube was built a small wooden housing; a brass plate could slide up and down just in front of the tube, and a slit in the brass could be adjusted exactly at the level of the water. The same brass plate carried the sighting-slits in the form of a cross, and in this way a horizontal line could be determined. To move the plates Hero once more used screws. The vertical screw came through the rod outside the housing and passed through a primitive nut—a smooth hole with a peg thrust in from the side so as to engage the screw thread. It was not possible at this time to cut in metal an internal thread of such small dimensions. The top of the screw was fitted into a cylinder fastened on the brass plate; a peg in the cylinder engaged a furrow in the head of the screw. The water-level was also provided with a plummet to set it vertical.

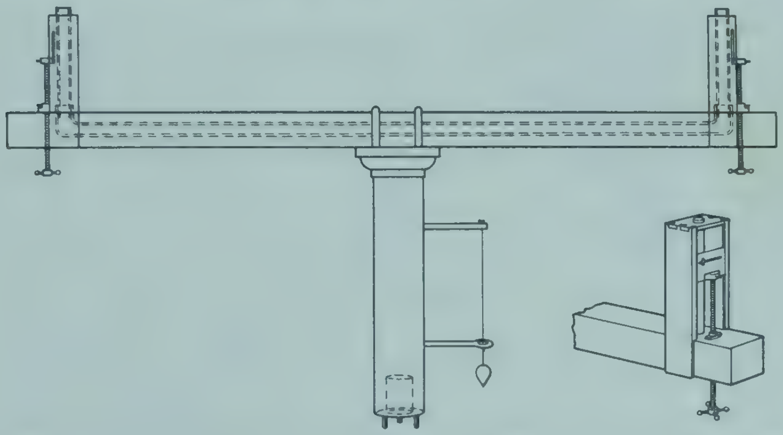
FIGURE 361—*Hero's dioptra: the water-level with* (inset) *one of the two sights.*

To use the water-level it was necessary to have two staves consisting of poles with plummets. Upon each a large target, painted half white and half black and sliding in a dove-tailed groove cut along the length of the staff, was raised and lowered by a string. A pointer on the target moved along a scale on the rod. To compare the height of two points it was necessary to set up a staff on each point, and then to place the dioptra on the line between them. When the slits had been adjusted the surveyor sighted one of the targets and had it raised or lowered by means of shouts or gestures, until the dividing-line was exactly on the sights. Then he looked through the dioptra the other way and had the other target adjusted. The difference in height between the targets, as read on the staffs, gave the difference in height between the two points. Then one staff was moved to the next point and the dioptra placed between the two points before repeating the procedure. The idea of turning the dioptra round and sighting many times from the same place does not seem to have occurred to the inventor.

Hero's dioptra remains unique, without past and without future: a fine but premature invention whose complexity exceeded the technical resources of its time.

VIII. INSTRUMENTS FOR COMPUTATION AND DEMONSTRATION

(a) *Globes and teaching-armillaries.* The use of a solid globe marked with stars and constellations to depict the celestial sphere is at least as old as the earliest Greek astronomers. An actual example dating from *c* 300 B.C. is preserved in a statue of Atlas now in the National Museum at Naples; the figure is 186 cm in height, and supports on its shoulders a marble globe 65 cm in diameter, engraved with circles and with diagrams of the usual representations of the major constellations. It seems likely that such globes were first constructed in this fashion merely as solid pictures and without any thought to their possible use for scientific record, teaching, or calculation. The next step is recorded by Ptolemy in the *Almagest* but might well date back to Hipparchus. Ptolemy describes how to make a celestial globe and mark it with the proper set of imaginary astronomical lines and to colour the surface dark, like the night sky, so that the stars will stand out properly in realistic fashion. Most important of all, Ptolemy describes how to mount the globe on an axis supported by a meridian which was in turn supported by an equatorial circle so that it might revolve to follow the diurnal rotation of the stars; and he inclines this axis according to the latitude of his observatory so that the visible celestial hemisphere shows above the plane of the horizon. This in all essentials is the modern celestial globe, and has undergone no major improvement between the time of Ptolemy and the present day.

The celestial globe seems to have had great popularity amongst the Muslim astronomers, and many texts survive to augment the information derivable from extant Arabic spheres. A brass globe made by Ptolemy himself, and a second silver globe made for the Caliph Adād al-Daula, were preserved in the public library at Cairo, according to a statement made by Ibn al-Nabdī in 1043. Unfortunately both these globes have been lost, and the oldest Muslim spheres are examples dated 1080 and a number from the thirteenth century and later. In Europe outside the Muslim region of influence, references to celestial spheres marked with the fixed stars are virtually non-existent until the revival of globe-making amongst the German school of instrument-makers towards the end of the fifteenth century. The subsequent developments belong mainly to the story of cartography.

A simpler type of celestial globe, showing the imaginary circles but not the stars or constellations, is found in a mural (*c* A.D. 50) from a villa at Boscoreale near Pompeii. This type of globe was developed later as the teaching-armillary, probably much influenced by Ptolemy's observing instrument, the armillary *astrolabon*, with which, however, it must not be confused. The teaching-armillary is known from manuscript miniatures of the thirteenth and fourteenth centuries. In its basic form it consists of a series of wire rings representing the equator, ecliptic, tropics, polar circles, solisticial colure, and other meridian circles (figure 362). The polar axis is usually extended to form a little handle which may be held by the teacher. In this form, or with slight improvements, it had great popularity throughout the Middle Ages and must have been frequently used as an adjunct to Sacrobosco's 'Sphere', the most-used text on elementary astronomy. During the sixteenth century teaching-armillaries were much elaborated by the addition of movable figures representing the planets, by the marking of star positions with little pointers, and by elegant craftsmanship and embellishment. They were a popular object for instrument-makers working under the patronage of noble and wealthy amateurs of science.

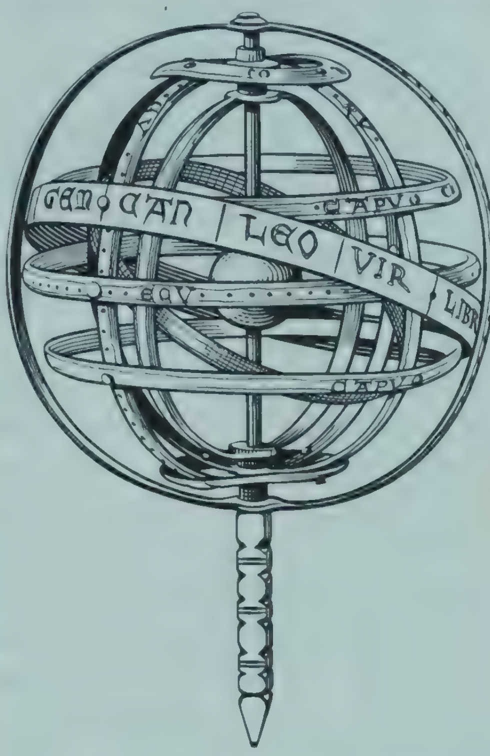

FIGURE 362—*Fifteenth-century armillary sphere, showing the Earth at the centre, the ecliptic (with signs of the zodiac), and other circles.*

Although the sphericity of the Earth was well known to the Greeks, the knowledge seems not to have resulted in anything more than a passing desire to make a terrestrial globe. Strabo reports that Crates, a contemporary of Hipparchus, made such a globe and exhibited it in Pergamum about 150 B.C.; he adds that such a globe was relatively so small that it did not have much advantage of representation over a flat map of the required accuracy. This probably accounts for the fact that little more about such globes is known from the Greeks, and nothing from the Arabs or from medieval Europe. It is not until the age of explorations that we hear of the first *Erdapfel* of Martin Behaim (1492), which inspired the German scientists and cartographers to follow his example. During the sixteenth century, terrestrial globes of all sizes and degrees of ornamentation become more and more common.

(b) *Calendrical and horary calculators.* The cyclical nature of the days of the week, the lunations of the Moon, and the seasons of the solar year make the calendar a natural subject for diagrammatic representation. Circular charts showing dominical letters, saints' days, and aids to paschal calculation are frequently found in European manuscripts from about the ninth century onwards. Many ingenious devices are used—for example, the annulus of John of Northampton—and from the thirteenth century such tables often consist of volvelles having one or more rotating disks. Probably the most common type of volvelle is that designed to show the phases of the Moon; it consists of two disks representing the zodiacal places of the Sun and Moon respectively. The upper disk carries a small excentric hole through which can be seen part of a blocked-in curve on the lower disk. This curve, often circular, is so placed that the part showing through the hole is similar in shape to the appropriate phase of the Moon for this particular elongation between the Sun and Moon. Using such a device one could easily determine the zodiacal place of the Moon by noting its phase and the known place of the Sun. This knowledge could then be used to tell the time at night. A remarkable instance of a Sun and Moon phase-calculator occurs on the dorsum of an Arabic astrolabe dated 1223–4; it includes a set of gear-wheels which turn the Sun and Moon disks at the correct speed when a calendar circle is adjusted to the date in the year.

The Moon phase-indicator is often combined with a nocturnal, which may consist of nothing more than a pointer added to that disk which records the position of the Sun (figure 363). The nocturnal is used for finding the time at night from the position of the circumpolar stars. The pole star is sighted through a hole at the centre of the disks and pointer, and the arm of the pointer is then adjusted to lie along the 'pointers' in the constellations Ursa Major or Minor.

(c) *Trigonometrical calculators.* Even the earliest Arabic astrolabes include on the dorsum one or more quadrants inscribed with devices to assist calculation by graphical means. A set of curves for determining unequal hours is often included, and even more frequently one finds a quadrant ruled with a series of horizontal and vertical lines. Such a reticulated quadrant is of great assistance, since it enables trigonometrical sines and cosines to be found graphically. This device occurs, but only rarely, in medieval European instruments, and by the fourteenth century one even finds sinical quadrants which contain this aid and nothing else. Later, in the sixteenth century, such calculators were made in larger quantities.

It is very interesting that the technique of computation by geometric construction received much attention from Greek astronomers. The Muslim astronomers, too, seem to have had great enthusiasm for all such devices, and many new forms and variations are known from their texts. The explanation is doubtless to be found in the tedious character of long computations, involving the sexagesimal system of notation, necessary for all astronomical work; the tedium was much increased by the habitual use of even eight or ten places of sexagesimals where two or three might have sufficed.

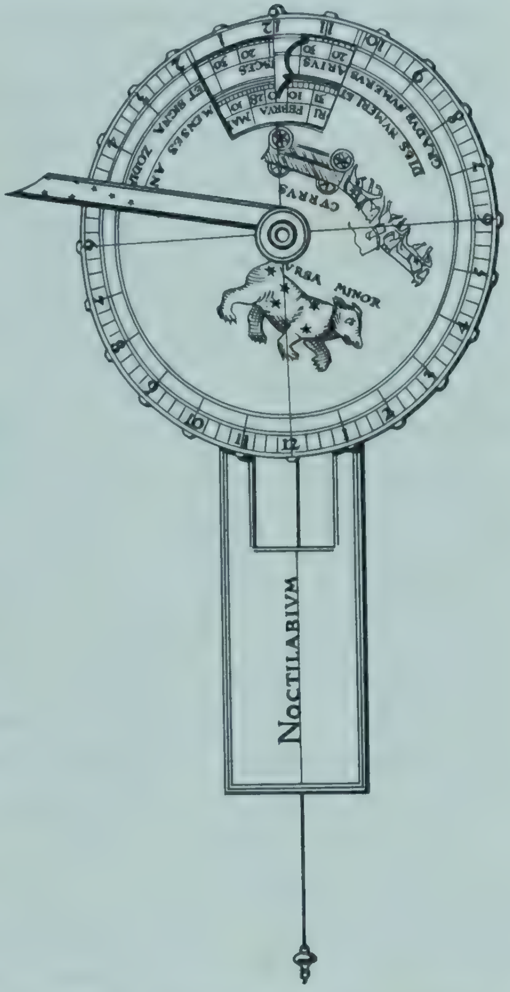

FIGURE 363—*Nocturnal by Georg Hartmann of Nuremberg. 1535.*

(d) *Planetary models and calculators.* The *Almagest* represents the apex of Greek attainment in pure science, and it is Ptolemy's planetary theory which forms the greater part of that work. Planetary theory was the most successful instance of the mathematical analysis of natural phenomena until very recent times, and this characteristic aspect of Ptolemaic astronomy reigned supreme and had the largest influence on men's minds until the seventeenth century. It is no exaggeration to say that the existence of this single overwhelming success in the pure sciences determined the whole course of scientific analysis through more than 1500 years.

Since this directing influence sprang from the accuracy of the planetary theory it was natural that much attention should be paid to the construction of models and devices that show the planets behaving according to rule, and reproducing the very courses of those planets as seen in the sky. The anaphoric clock has already been described (p 604) as perhaps the first artificial model of the movements of the heavens; it was succeeded by other models including representations of the planets as well. The mechanical clock indeed owes its origin to the desire to exhibit more complex models, which would demonstrate the glory of God as revealed in the perfection of regularity in the complicated motions of the heavens. The first great public clocks usually showed more resemblance to gigantic planetaria or orreries than to the modern timekeepers.

Another type of planetary device was intended for professional use rather than public gaze. Although Ptolemaic planetary theory achieves its success by fairly simple geometrical construction, it results in lengthy calculations and many references to tables if used for computing the position of a planet at some particular time, say for casting a horoscope. It has already been remarked that the Muslim astronomers were particularly enthusiastic about graphical methods of computation, and it is not surprising that they adapted them to planetary problems. The method used was the straightforward one of simulating the proper geometric construction by circles and straight lines engraved on plates of wood and metal, with movable bars and stretched strings to provide the variable lines of the geometrical figures. Such an instrument is usually called an equatorium, because it 'equates' or computes the positions of the planets.

The earliest texts on the equatorium have come to us through the archaic Castilian of the Alfonsine *Libros del Saber*, which translates Arabic texts by Abulcacim Abnacahm[1] (d 1035) and by Al-Zarqālī (1029–87). The former gives the instrument in the most primitive and inconvenient form possible; a separate brass plate is used for each planet, and this plate is engraved with a number of graduated circles. Al-Zarqālī improves the technique by arranging half the planets on each side of a single plate, but his device still includes a large number of divided circles, made rather confusing by the small space into which they are packed. The equatorium was taken up and further improved by the ablest European astronomers of the thirteenth and fourteenth centuries. John Campanus of Novarra (*c* 1261–92) is said to have been the first to write on the device. A slightly more convenient form was devised by John of Linières (fl Paris *c* 1320–50), who placed all the planetary circles on one side of the plate and reduced the confusion by making one graduated circle serve for all the angles to be laid off. His treatise on the instrument was often included with the canon to his version of the Alfonsine tables, which was the standard work on the subject from about 1320 until the time of Regiomontanus.

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[1] Abū'l-Qāsim ibn al-Samḥ, of Granada.

The Merton College astronomers seem to have valued the equatorium as a most important instrument, and as a necessary complement to the astrolabe. The only surviving medieval example of the device is preserved there; it was probably given to the college by Simon Bredon (d 1372), who may have also written a Latin version of an Arabic tract on the subject. Another variation on the fundamental design is the albion, invented by Richard of Wallingford in 1326, which reverts to the original design by having a separate plate for each planet, but makes the instrument more manageable by arranging the plates within a *mater* designed in the fashion of an astrolabe.

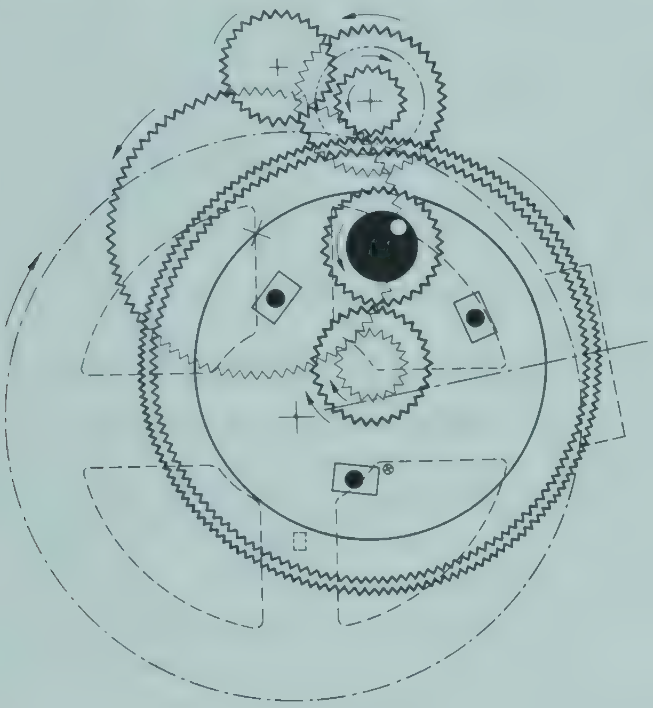

FIGURE 364—*Reconstruction of the fragments of an instrument found at Antikythera in the form of a planetary calculator or model.*

The most economical and efficient type of equatorium is described in a tract in Middle English, 'The Equatorie of the Planetis', which is dated 1392 and is thought to be a holograph work by Geoffrey Chaucer (d 1400) written to supplement his 'Treatise on the Astrolabe' (1391). In this form there are only two inscribed circles, and the design shows the greatest economy and ease of use.

The Persian astronomer, Al-Kāshī (d 1436), extended the principle of the instrument to the more complicated problems of computing the ecliptic latitude, as well as the longitude, of the planets, and of determining data for eclipses of all degrees. Similar extensions and simplifications were introduced by many astronomers and mathematicians throughout the fifteenth and sixteenth centuries, and indeed the equatorium seems to have provided a favourite target for the exercise of geometrical and mechanical ingenuity of a high order.

(e) *The 'Antikythera' machine.* In 1902 archaeologists, working on the wreck of a treasure-ship off the coast of the island of Antikythera between Greece and Crete, dredged up from the sea-bed four fragments of highly corroded copper showing vestiges of what had clearly been a piece of complicated geared clockwork. The fragments (figure 364) are now in the National Museum in Athens, and present a most important piece of direct evidence for the attainments of Greek science in instrument-making. The fragments have been variously dated between the first century B.C. and the third A.D. Whatever the date within that range, it is still very surprising that an artifact of such mechanical complexity should have existed; nothing comparable is known either by example or by description in any extant text.

Inscriptions on the fragments, only partly legible, make it evident that the device was in some way concerned with the motions of the Sun, the Moon, and the planets. It seems likely that the instrument was a moving model of the planets—a sort of orrery—and that the function of the complex gearing was to reproduce the motions in the excentric circles and epicycles of the Ptolemaic system. It is natural that there should have been some attempt to make such a model for demonstration (p 616) and the construction of quite complicated automatic jacks and mechanisms was already familiar to Hero. The gear-work on this Antikythera machine shows a style of construction and a mastery of technique that would not have been out of place in a good workshop of the seventeenth century. It is one of the greatest enigmas in the history of technology that these badly preserved remains of a Greek machine should present features so far in advance of anything else known from classical times.

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A medieval astronomer making an instrument. Richard of Wallingford (c *1292–1335*), *a member of the 'Merton school'* (*pp 585, 617*) *and the first Latin writer on trigonometry, is shown dividing a circle. On the table are anvil, hammer, and square. A quadrant hangs in the cupboard. Richard's face is shown spotted because he suffered from 'leprosy'. From a fourteenth-century manuscript.*

23

THE MANUFACTURE OF SCIENTIFIC INSTRUMENTS

FROM *c* 1500 TO *c* 1700

DEREK J. PRICE

I. THE FIRST SPECIALIST CRAFTSMEN

IT is a truism that the modern scientist is a man of the laboratory. He uses scientific instruments and apparatus to extend observation beyond the range of his unaided senses, and to create powers of manipulation greater than those of his bare hands. It has not always been so; indeed, one of the most significant factors in the scientific revolution of the seventeenth century was the development of new tools for the scientist, which opened new worlds to his experience.

Probably the most interesting link between the histories of science and technology is the way in which science has ploughed back her profits by creating instruments to be used for further scientific work or for the application of science to practical purposes. There are already many accounts of these instruments, which serve to illuminate the history of science by explaining how knowledge led to new instruments and how such new instruments led to the acquisition of further knowledge. It is the object of this chapter to describe the technological factors associated with the rise of the craft of instrument-making in its great formative period in the seventeenth and eighteenth centuries.

Medieval scientists had few instruments at their command. Some devices, like the balance, the furnace, drawing-compasses, and dividers were already ancient and could readily be obtained from craftsmen. Other instruments, such as astrolabes, sun-dials, astronomical observing-instruments, and calculators were more complex and depended on scholarly appreciation of a manuscript tradition. The scientist might be able to employ a carpenter or metal-worker to do the rough construction, but the detailed planning, the engraving, and the graduation he must needs do himself.

The coming of the printed book and the revival of Greek mathematics and astronomy during the last quarter of the fifteenth century had a profound effect on instrument-making. Rapid dissemination of the new-found learning created an intensified demand for the traditional instruments, and texts describing their construction became more readily available. At the same time there was a conscious move by the scientists towards the employment of more specialized artisans, capable of carrying out fine work as well as crude, and able to produce these instruments with the minimum of assistance from the astronomer or mathematician himself, who thus became a designer simply. A craftsman could be shown the scientific principles, or could copy the pattern of any instrument such as a pocket sun-dial or an astrolabe; he could adapt the mechanical and practical design to his materials and to the techniques at his disposal. This done, he was capable of turning out a large number of similar instruments, though of varying size, decoration, and elaboration.

Thus by the beginning of the sixteenth century there were two distinct types of instrument-makers. On the one hand there were scientists (mainly astronomers) whose special interest was in the design and actual making of instruments. On the other hand there were whole dynasties of craftsmen who learned to turn out large numbers of special types of the more popular varieties of instruments. Both forms of activity at first centred on Nuremberg and its surrounding region, including especially the sister-town of Augsburg (p 585). Here the guilds of artists and craftsmen were extraordinarily well developed, and their members possessed in high degree the necessary techniques of fine working and engraving alike on metal and on ivory.

It took about a century for the increased interest in instruments to spread to the rest of western Europe. By the last quarter of the sixteenth century both scholar and craftsman instrument-makers were numerous in England, France, Italy, and the Low Countries, as well as in Germany. It is particularly interesting to trace the diverse stimuli in the transmission of the craft from place to place. Augsburg rose to a prominence comparable with that of Nuremberg partly because of the money poured into its workshops as a result of large orders for special instruments from the Danish astronomer Tycho Brahe (1546–1601). Erasmus Habermel at Prague made a prodigious number of highly original instruments under the active patronage of the erratic Emperor Rudolph II (1552–1612) and Franciscus Paduanius of Forli (1543–16—?), his physician. A refugee, Thomas Gemini (fl 1524–62), perhaps connected with Arsenius's Louvain workshop, brought his craft of engraving to England at just the time when sheet brass was first being made in this country (p 586). The organization of craft-workers in London was particularly well adapted to the master–apprentice method of instruction in the complicated business of instrument-making. The trade flourished here and workshops multiplied rapidly; in other countries the seed fell on less fertile ground or the organization was destroyed in times of war and unrest—as, for example, in Germany itself, where the Thirty Years War brought the workshops of Nuremberg and Augsburg to a meagre end in which only shoddy and stereotyped instruments were produced.

II. TOOLS FOR PRACTITIONERS

The spread of instrument-making from scholar to artisan was quickly followed by a similar spread in the use of instruments. Here again the stimulus was partly due to printed books which, besides explaining the design of instruments, revealed the manner of their use. More important was the influence of social changes, which led to a demand for the survey of estates as they were redistributed, of military techniques, which placed an emphasis on more accurate gunnery, and of the great maritime explorations, which led to a much increased interest in navigational methods and instruments. These stimuli, together with the more general availability of scientific knowledge, produced a new class of men, the 'practitioners'. They were by no means scholars in the normal sense, but they had sufficient technical knowledge to use surveying-, gunnery-, and navigation-instruments, and in many cases they augmented their living by teaching the practice of the instruments and the elementary mathematical principles on which it rested. The practitioners were the first fully conscious exponents and teachers of technical science; they did much to form the idea, so often expressed in the scientific revolution, that science was not only an intellectual pursuit but a potential source of much practical good to the individual and to the state.

A large part of the business of the artisan instrument-maker lay in the production of instruments for the practitioners. Some of them were even practitioners themselves, demonstrating and using the instruments and writing about them, advertising themselves and their wares; they worked hard, but sad personal notes in their writings show that many found little monetary reward and died in penury. They were a close-knit group, partly because of the apprenticeship system necessary for the specialized craft, partly because they congregated their shops and workshops in highly localized districts—a convenient system followed by many older trades. Outside these areas there were even more specialized makers of instruments, who set up business in places dictated by their custom. Thus makers of navigation-instruments were to be found near the shipyards, wharfs, and docks, and gunnery-instruments were made in or near the national armouries. A few fortunate artisans of exceptional skill were patronized by the state or by some eminent scholar, and were wholly or partly maintained to produce instruments for some special purpose.

The chief materials used for instrument-making before *c* 1650 were wood and brass, though ivory, leather, and vellum might also be employed for the making of an object that was to receive much decoration. Engraved ivory could be coloured, while vellum and leather could be stamped and gilded by bookbinders' methods. There seems to have been a cleavage between the artisans using wood only and those using brass for the greater part of their instruments. Probably the 'makers of instruments in wood' had developed, and were still trained, rather as carpenters, joiners, or turners than as metal-workers or engravers. Apart from the division of their scales, the instruments involved technical methods common to other wood-working of the period. The woods used were the close-grained varieties—box, beech, and pear—normally adopted for all fine work.

The 'makers of instruments in brass' were principally engravers, and fine-metal workers only secondarily. This is particularly evident in the range of instruments produced, and it seems to have had some considerable effect on the evolution of design. Whenever possible, a device was made by shaping a flat metal plate and engraving lines and scales on it; the plate might be combined with others similarly made, but specially shaped or moulded components were avoided unless absolutely essential. The techniques applied to such simple instruments were therefore those of the engraver together with ordinary hammering, cutting, and filing to shape the brass plates (figure 365). All the finest artisans, however, especially those working on instruments for patrons who demanded an object of beauty, prided themselves on their proficiency in the more complex arts of metal-work. In such cases they seem to have borrowed the techniques of the goldsmith and other decorative metal-workers, producing

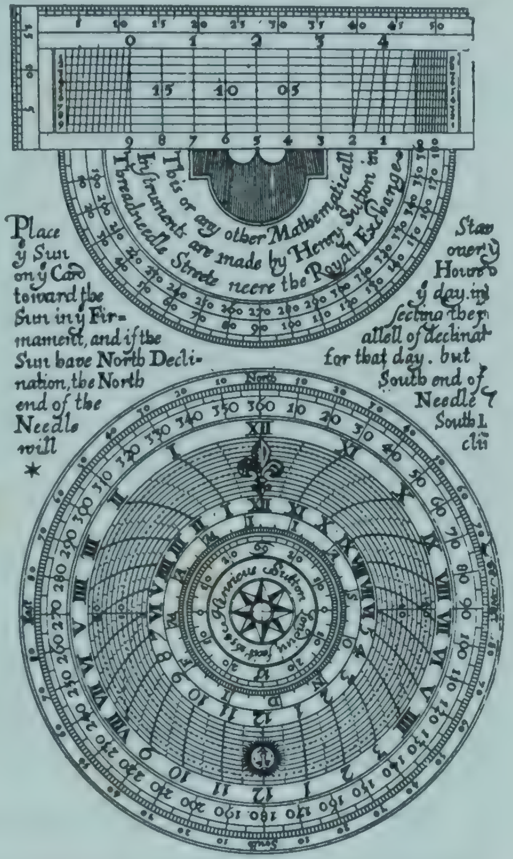
This or any other Mathematicall Instruments are made by Henry Sutton in Threadneedle Streete neere the Royall Exchange
Place ÿ Sun on ÿ Card toward the Sun in ÿ Firmament, and if the Sun have North Declination, the North end of the Needle will *
Stan over ÿ Houre ÿ day in section the allell of declinat for that day. but South end of Needle South declin
North
XII

FIGURE 365—*Trade-card of Henry Sutton (1654), showing* (above) *a protractor and* (below) *a sun-dial.*

involved shapes, ornamental mouldings, and so forth. This is especially noticeable in the case of pocket sun-dials, astrolabes, armillary spheres, and some of the finer gunnery instruments.

The all-important scales and graduations were determined by measurement, calculation, and geometrical construction, and numerals for the scales as well as lettering were often punched on the plate. Sets of such punches seem to have been handed down from workman to workman, and it is often possible to identify the products of a particular school by peculiarities of the stamped characters as much as by the general style of metal-work and engraving. Undoubtedly the most important feature of any instrument was the careful accuracy with which the graduations and engraved lines were laid out. Here again, only the simplest techniques were used. In addition to the ordinary graving-tools for incising fine lines—there was no broad graver then—they had only scribing-compasses, plain or fitted with a screw opening adjustment, and beam-compasses for the arcs of larger radius. Crude tools could produce high craftsmanship only by the exercise of meticulous care, and it is not uncommon to find trial graduations and constructions faintly showing on the face of the instrument or, more clearly, on the hidden backs of the main plates.

There were no sophisticated methods for graduating rectilinear or circular scales. If elementary geometrical construction would not suffice, marks were set according to calculation or by trial and error. For the division of the circle, repeated bisection of six 60°-angles gave arcs of 15°; these were then subdivided by trial stepping with dividers.

III. INSTRUMENT-DESIGN BEFORE 1650

To understand the development of instrument-design during the period of the scientific revolution it is essential to distinguish between the three main groups of people concerned with instruments and their use. The first and largest group was that of the artisans with their general, everyday trade of producing instruments for the practitioners or making more elaborate, costly, decorated instruments for their patrons and richer clients. Secondly, there were the scientist instrument-makers embodying their own devices, unaided or with some assistance from a workman in the manual labour. Thirdly, there was a small intermediate class of specialists making, for example, ships' compasses at some particular shipyard, or gunnery instruments at some state armoury.

If one wishes to study the radical improvements in scientific function of the instruments, and the introduction of quite new devices, these may be found in the published works of the scientists. Such information is readily accessible, yet may be misleading because it does not necessarily follow that the instrument was adopted in practice, or even that it was accepted by other scholars. It was quite common for general use to be delayed for several decades, or even for centuries, after the original invention. To investigate the history of instrument-technique it is essential to supplement learned treatises by the writings of the practitioners and, above all, by the evidence afforded by instruments that have been preserved.

The basic selection of instruments produced by the artisans was related to classical designs. Quadrants, astrolabes, armillary and other spheres, besides all varieties of sun-dial, were made in great profusion and elaborated in scientific principle and mechanical construction. More direct improvement was made in the observatory instruments demanded by the great astronomers of the period. General tendencies can readily be seen in the devices used by Tycho Brahe and by Johann Hevelius (1611–87). All instruments had to be divided finely and carefully; they also had to be as large and as rigid as the strength of their materials permitted, compatible with the necessity of providing accurate pivots and bearings for the moving parts. Large instruments were sometimes made of wood covered with strips or sheets of brass in order to avoid serious difficulties of weight, and devices both large and small were rendered lighter by cutting away the redundant areas of metal plate, leaving only struts to support, for example, the divided limb of a quadrant.

Navigation-instruments were sturdily built and of simple design. The cross-staff or 'Jacob's staff' (figure 340) of the astronomer was widely adopted at sea; it possessed the great advantage of using a linear scale, so much easier to graduate than a circle. Towards the end of the sixteenth century the back-staff or Davis's quadrant (figure 341) was introduced, using a similar principle, but enabling the navigator to sight on a shadow cast by the Sun and so avoid the danger and difficulty of direct observation in the Sun's glare. The nocturnal was also taken from the range of astronomical instruments into common use, and became useful as a means of telling the running-time at night from the rotation of the circumpolar constellations. The staffs and nocturnals were all produced by the wood-working instrument-makers; they were reasonably cheap and sturdy, though the accuracy of graduation is sometimes poor. The mariner's astrolabe was a Spanish-Portugese adaptation of the astronomer's (planispheric) astrolabe, probably invented *c* 1535 and popular for about a century thereafter. It is important as the first scientific device made solely for navigational use, and it seems to have been made by specialist foundry-men and engravers in the shipyards (p 608).

The magnetic compass was much employed, on land as well as at sea. The earliest surviving examples are found on portable sun-dials for travellers (p 600)—the needle serving the double purpose of guiding the traveller and orientating the gnomon—and on miners' dials used for setting underground galleries. There is, however, plenty of contemporary evidence to assure us that some sort of magnetic compass was in early use at sea. Whereas mariners' and miners' compasses were made by specialist craftsmen, compass sun-dials were the work of general artisans. Considerable ingenuity was exercised in the design and mounting of the magnetic needle, all sorts of shapes and pivots being used, successful methods no doubt being handed down as trade secrets together with the lodestones used for magnetizing the needles and retouching them. To seal the compass from dust, and to prevent the needle from jumping off its pivot, it was usual to cover the compass-box with a thin sheet of transparent material—in early

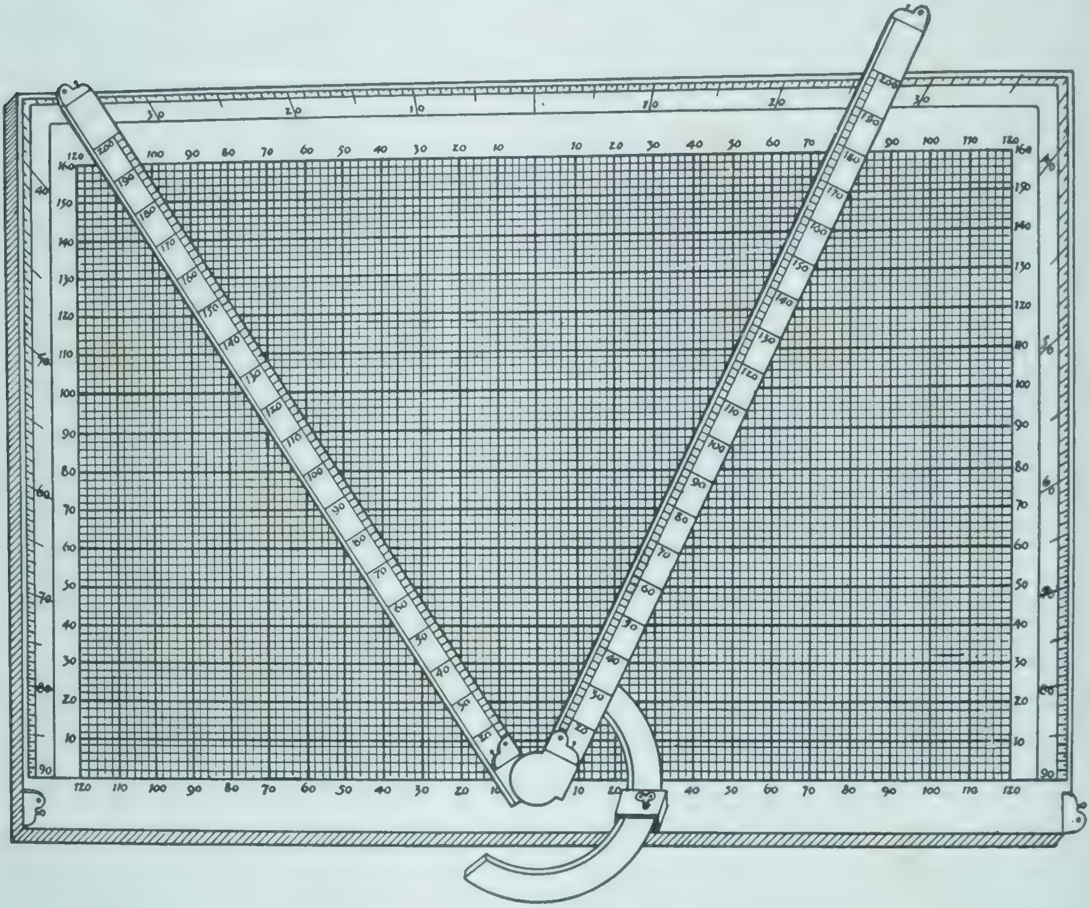

FIGURE 366—*Bramer's* trigonometria *(1617), a triangulation instrument. The lengths of two known sides of a triangle (with their included angle) are set out by proportion on the movable, graduated alidades. The length of the unknown side is computed by Pythagoras' theorem from the lengths intercepted on the network of parallels.*

times mica, in later ones glass. The mounting of the window and its retention by a circle of springy wire were later taken over and applied to lenses in the first optical instruments. Earlier spectacle- and reading-lenses had been mounted in frames cut from horn or leather.

The first surveying-instruments were again modifications of older astronomical measuring-devices; in particular the makers adopted the alidade and circular angle-scale found on the *dorsum* of astrolabes (p 608), adding to the instrument a socket by which the surveyor could mount it upon a tripod stand or a staff to hold the instrument steady in the field. With the addition of a magnetic compass for taking bearings, this became the circumferentor or 'Dutch circle', a semicircular modification of which—cheaper because only half as much graduation was needed—was called the graphometer. Perhaps by combining circumferentors in vertical and horizontal planes, perhaps as a direct adaptation of the torquetum (p 593), the theodolite was evolved as a universal surveying-instrument (p 541). Yet the development of the theodolite was not the only advance in surveying-instruments; even more important at the time was the invention of a number of devices avoiding the trigonometrical calculations involved in solving the surveyed triangles. Considerable effort was directed to the perfection of such contrivances as the *trigonometria* (figure 366) of Benjamin Bramer (1588–1650), which incorporate a grid or scales enabling the unknown lengths and angles to be read without computation.

Computing- and calculating-devices were most important in an age when mathematical symbolism and arithmetical technique were crude and more difficult to master than the taking of measurements. Several types of measuring-rule were designed for gauging the contents of barrels, the range of shots, the value of bullion, and so on, and such devices as 'Napier's rods' were used to assist ordinary numerical operations. In the seventeenth century geared calculating-machines were invented by Blaise Pascal (1623–62) and others. The most important mathematical instrument was undoubtedly the sector, a hinged and graduated rule which enabled a wide variety of computations to be made by the theory of similar triangles. Graduated drawing-compasses for gauging had been familiar in gunnery and dialling for some decades, but the sector was put into its versatile form by Galileo (1564–1642) (figure 367) and his workman Marcantonio Mazzoleni, towards the end of the sixteenth century. It was used in combination with a pair of dividers, the hinged arms of the sector being opened to a suitable distance and lengths measured on the engraved radial scales. A wide variety of radial scales—natural numbers, squares, cubes, reciprocals, chords, tangents, densities, and many others—is possible, and standard selections became associated with the English, French, and Italian types of instrument. The sector remained very popular for calculations in gunnery, surveying, dialling, and gauging, in spite of competition from the slide-rule after that device had been invented about the middle of the seventeenth century. The logarithmic slide-rule did not completely displace the sector until late in the eighteenth century; indeed, the sector was included as a standard instrument in drawing-sets and in navigation equipment until well into the nineteenth century.

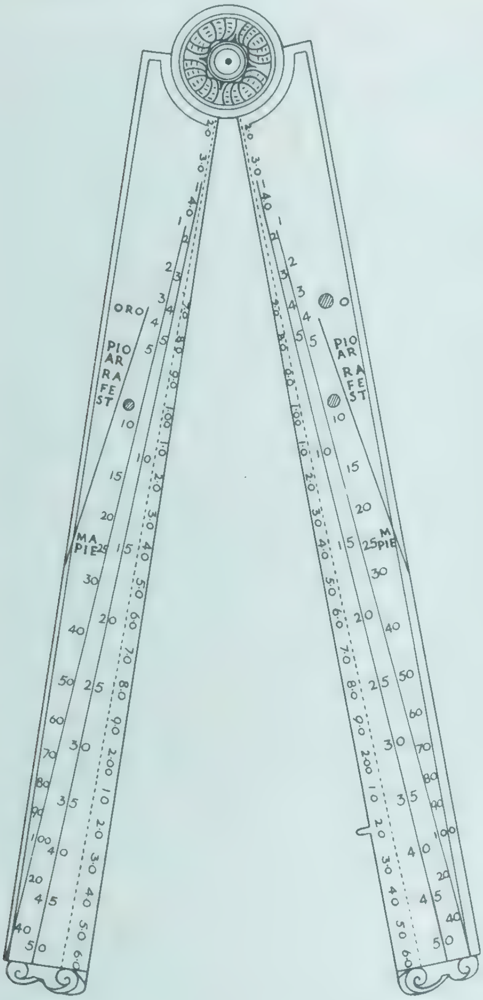

FIGURE 367—*Galileo's 'geometrical and military compass', an early form of the sector. The various divided lines permit numerical calculations, calculations involving the densities of the metals, etc.*

The first instrument of mechanical rather than scientific complexity to become generally available was the hodometer or taximeter. In its elementary form it was merely a click-mechanism for counting the revolutions made by a carriage-wheel of known circumference—a device familiar from the writings of Vitruvius (p 512), though there is doubt whether the instrument was ever actually made and used in ancient times. During the later sixteenth century the hodometer was much elaborated by the addition of a magnetic compass and by a recording-device fitted to the more refined models. This was the first self-registering instrument. It operated by a trident of spikes above the compass-needle; after every 10 or 100 revolutions of the measuring-wheel a trip-lever elevated the needle and pressed the trident into a paper strip which was then moved on to be ready for the next record of the direction in which the carriage was moving. Theoretically, one could drive round a large estate and subsequently map the path taken. In reality, accuracy cannot have been high, but technically the instrument is important as an indication of the change in practice brought about by the introduction of the methods of the clock-maker.

Perhaps the finest precision instruments were those made by the specialist artisans concerned with gunnery. Quadrants, levels, and gauges made by such craftsmen as Christopher Trechsler (fl 1571–1624) of the Dresden armoury show clearly that much attention was paid to accuracy in the planeness of surfaces and the fit of sliding parts. Another interesting feature was the use of screw-adjustments for fine motion (plate 25); the threaded screw as a fixing-device is a comparatively late development in instruments (p 657). It may have been used earlier for the fastening of jewelry but does not appear otherwise until the middle of the sixteenth century, when crude screws are found in the fittings of armour. Quite probably it was then introduced into other armoury-devices, and from these to general instruments and clockwork. Before the screw came into use, soldering, rivets, and wedge-fittings were the normal means of fixing metal parts together. The screw as a slow-motion device and as a worm-gear is of much earlier, probably Hellenistic, origin (p 610).

IV. THE DIVERSIFICATION OF INSTRUMENTS

From about 1650 onwards the full impact of the scientific revolution manifested itself in the instrument-making trade by great changes in its scale and scope. The rapidly growing group of amateurs of science, and the scientific academies into which they were soon organized, combined with the practitioners to afford a considerable market for instruments. In the past each instrument had been built to order, according to the demands of the patron or the inventive craftsmanship of the maker. During the seventeenth century there was a tendency for new devices or new variants of old devices to achieve sudden popularity through published accounts in books and scientific journals, and through reports that spread rapidly among the ranks of the amateurs. Thus there would arise a large demand for each of these types of instrument, a demand that could be met only by mass-production. Although the trade was expanding as fast as its market, or even faster, the need for a large output increasingly forced the craftsman to specialize in a limited range of instruments at any one time, and to make this range in quantity. During this period the scientific instrument ceased to be an individual work of art-craftsmanship, and there was a noticeable tendency for the maker merely to sign, rather than to sign and date, his products: the artist's subscription was changing into the trade-mark. Although instruments became less artistic, specialization and quantity-production led to a considerable improvement in their technical details and in the precision engineering involved. A secondary effect of specialization was that instrument-makers' shops frequently sold not only the products of the master and his workmen but also those of other craftsmen producing many different types of instrument.

Occasionally, articles were imported from foreign workshops and engraved with the name of the artisan or shopkeeper who acted as an agent.

The greatest effect of the scientific revolution was wrought by new inventions and discoveries that led to the manufacture of instruments radically different from any which had been made before. Conspicuous among these were the optical instruments—the telescope and microscope—but at the same time the evolution of new practitioners' instruments for surveying, navigation, and gunnery was proceeding rapidly, and the wider horizons of physical science led the instrument-maker to produce, for example, thermometers, barometers and air-pumps, magnetic compasses and mounted lodestones, pantographs, and cases of draughtsman's instruments.

The old instruments, based primarily on the astrolabe, quadrant, and the wide range of sun-dials, consisted chiefly of simple engraved plates, but the new optical and physical instruments were widely different in construction and enforced quite new skills upon the trade. Thus the instrument-maker ceased to be a specialist in the art of engraving and had to take upon himself the tasks of more complex metal-working and machining, wood-working and turning, glass-working, and tube-making. In this he was helped by the fact that other trades were already using such techniques and, from the middle of the seventeenth century onwards, instrument-makers are closely allied with the London livery companies of the Clockmakers (chartered in 1631) and the Spectaclemakers (1629), the manufacturers of common measuring-rules, cabinet makers and joiners, glass-blowers, and other craftsmen. The first of these alliances was so strong that in England the principal group of mathematical instrument-makers joined the Clockmakers *en bloc* in 1667, though Elias Allen, 'Doyen of the Mathematical Instrument Makers' Club' (plate 26 B), had been a master of the Company since 1636 and had been regarded as one of its leading members. Later, when many of the makers of telescopes and microscopes had become organized under the Spectaclemakers, there developed considerable friction between them and those of their colleagues who had become master clockmakers or had claimed that neither of the companies was concerned with their craft. During this period a gap seems to have developed between the makers of mathematical and of optical instruments, and this division, together with that already existing between those who worked in metal and those in wood, produced a much disunited trade, served to increase specialization, and prevented the rise of general instrument-shops.

The increase in numbers and specialization of the artisans led them into a new relationship with their patrons and customers, and with designers and scientists.

Instead of being largely supported by a single patron, the craftsman had become a shopkeeper selling his goods to a large clientele. Instead of working under the direction of a single scientist, he had access to many. Special relationships are still evident, as when Elias Allen (fl 1606–54) was taught how to make the new circular slide-rule by its inventor, William Oughtred (1575–1660); and many people were still practitioners devising their own instruments and having them made by their own special workmen. Much more important, however, is the fact that the instrument-makers became a focus for much of the day-to-day scientific activity of the time. Their shops became meeting-places for both scientists and amateurs, and they played a part in the scientific correspondence which was then vital in the dissemination of new ideas. The taverns frequented by the artisans, and later the coffee-houses, played similar roles. The diary of Robert Hooke (1635–1703) records an almost daily visit to some place where instrument-makers and their customers met. It is especially interesting that, in some countries at least, this type of organization around the instrument-makers seems to have been highly active long before the formal meetings of the scientists and amateurs who later constituted the Royal Society and the scientific academies in other lands.

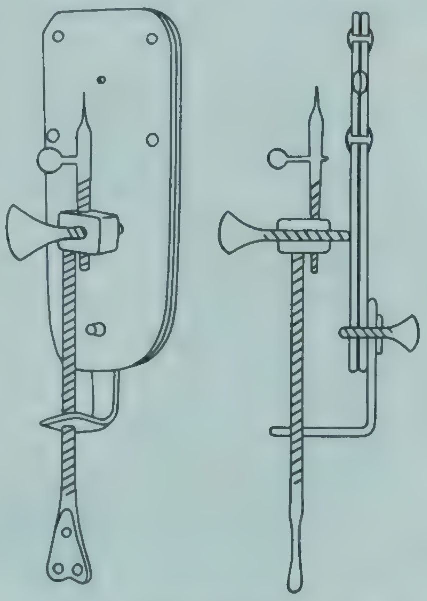

FIGURE 368—*Diagrammatic views of a Leeuwenhoek microscope. The spherical lens is clamped in little pierced recesses between two brass plates. The object is mounted on the point, which is brought into focus by means of the rather coarse screws.*

V. THE NEW OPTICAL INSTRUMENTS

The telescope and microscope were introduced into Holland at the beginning of the seventeenth century, perhaps as a result of casual experiment by practical spectacle-makers.[1] Within a few years Galileo had seized on the idea, probably rediscovering the necessary combination of lenses himself, and soon afterwards he announced very remarkable and entirely unprecedented celestial observations made with his first telescopes. For many years telescopes made in his workshop were greatly prized. Galileo's observations—soon extended by others—aroused enormous enthusiasm and provoked wide controversy; there can scarcely have been another period in the history of science when so much new information came at one time—the discoveries of Saturn's rings, Jupiter's satellites, the phases of Venus, the spots on the Sun, the mountains on the Moon. In view of this great interest it is surprising that so little happened after the first flush of enthusiasm had died away, for a whole generation intervened before the telescope and compound microscope were accepted as popular instruments. In the meantime they were little more than scientific toys, though Christopher Scheiner (1575–1650) investigated sunspots thoroughly and Francesco Stelluti (1577–1653) used the microscope to produce very fine drawings of insect anatomy. Not until about 1660 does one find instrument-makers beginning to

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[1] For a different opinion, see p 231. For applied optics generally, see ch 9, section VI (p 229).

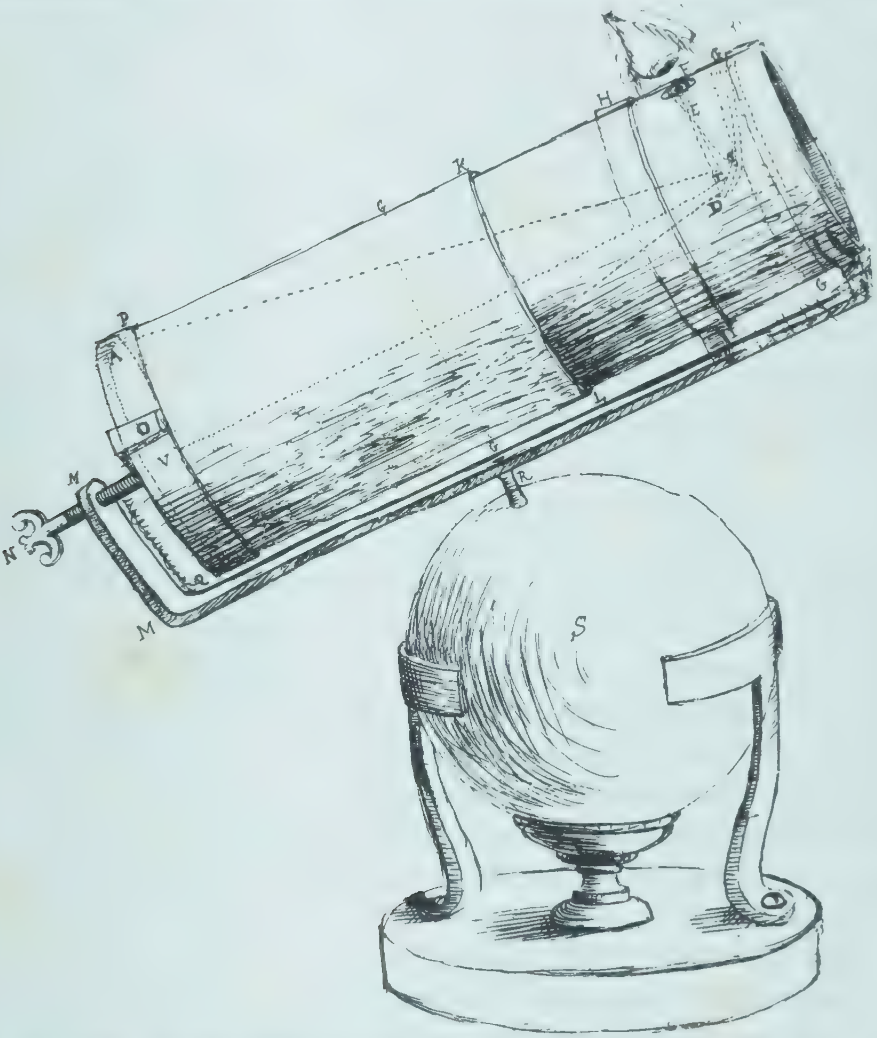


FIGURE 369—*Newton's original drawing of his reflecting telescope, 1672. Light entering the tube is reflected by the concave metal speculum* (A) *to the flat mirror* (D)*; here it is reflected through the eye-lens* (F) *to the eye. The telescope is focused by the screw* (N) *which varies the distance of the speculum from the mirror.*

make telescopes and compound microscopes as a regular trade, and even then it took another decade for anything approaching large-scale production to be set on foot. The lack of suitable workmen must have been a not inconsiderable factor in the surprisingly slow acceptance of devices so novel and arresting.

The technical difficulties that faced the first commercial makers of compound microscopes and small telescopes related to the body of the instrument rather than to its optical components. Optical design and the provision of suitable lenses may have been of overriding scientific importance, but by this time reasonably good glass was available, lens-grinding was highly developed in the spectacle-making industry, and the study of geometrical optics was sufficiently advanced. During the seventeenth century there was much progress, especially in the grinding of very small lenses—for example, by the amateur Leeuwenhoek (1632–1723), in his superlative simple microscopes (figure 368) with which he was able to see spermatozoa and even some bacteria—and of very large lenses for the more powerful telescopes demanded. Other important optical improvements were the introduction of an erecting eye-piece for the terrestrial telescope by Schyrlaeus de Rheita *c* 1645, the use of multiple lens-systems in microscopes after about 1650, and later still the far-reaching invention of the achromatic lens, thought impossible by Newton, but finally achieved by Chester Moor Hall (an amateur) in 1729 and carried into production by the great optical instrument-maker John Dollond (1706–61) in 1758. Until then, the severe consequences of chromatic aberration could be avoided only by substituting reflecting mirrors for refracting lenses, and from the first construction of a reflecting telescope by Newton there developed considerable activity, soon spreading to the professional instrument-makers. Newton's first reflector (figure 369) shows well the characteristics of prototype instruments made by scientists at this period;

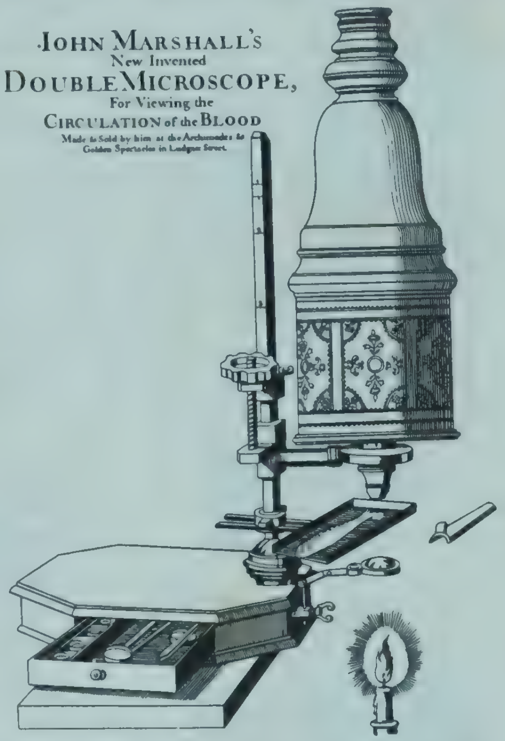
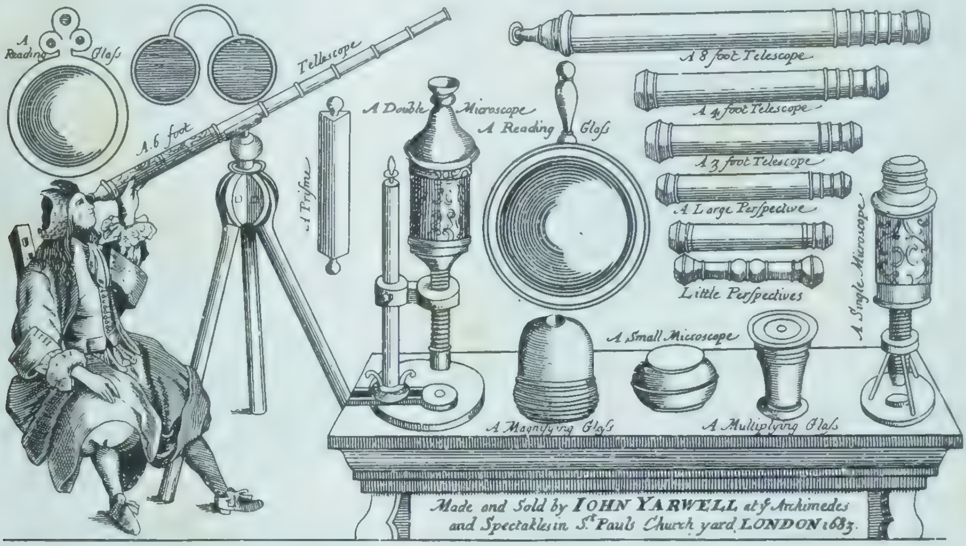


FIGURE 370—*John Marshall's microscope, as illustrated in 1704. The large body contains two lenses; the objectives are fitted in interchangeable brass mounts screwed to it. The arm carrying the body slides on the brass pillar; when locked in position by a set-screw, adjustment is made by the lead-screw turned by the knob. The pillar inclines on a ball-joint fixing it to the box base.*

the mechanical design includes novel features, such as a sphere constituting a universal mounting, the sliding tube which gives a crude but sufficient way of focusing, and the method of mounting the all-important mirror. We know from Newton's manuscripts that he spent much time in experimenting to find the best speculum metal and the optimum method of figuring it successfully. Similar experiments were made by subsequent professional makers of telescope-mirrors, and this activity became of major importance, such artisans gaining or losing their reputations by the standard of their success in the art of figuring the surfaces to produce instruments with excellent definition and little trouble from tarnishing.



Much more difficult for the artisans were the problems of mechanical design and construction involved in mounting the optical parts. The mounts for the lenses were usually made by wood-turning, which may account for the fact that one of the most distinguished early makers of microscopes in England, John Marshall (1663–1725), entered the trade after apprenticeship as a turner (figure 370). The tubes in which the mounts were centred created greater difficulties; they had to be accurately made so as to slide smoothly for focusing, and in telescopes they had to be reasonably light—though Galileo's first instrument had used a tube of lead. Tubes of rolled parchment or pasteboard were widely employed, and these were frequently decorated by stamping, colouring, and gilding, arts borrowed from the bookbinder (figures 371, 372). Tubes consisting of lengths of wooden moulding were less common, but very long telescopes were sometimes made from four planks fitted together to give a square-section tube to which eyepiece and objective mounts could be strapped (tailpiece, p 244). The excessively long telescopes introduced in an effort to minimize spherical aberration became so ungainly—being a hundred or more feet long—that tubes were abolished altogether, and in an 'aerial telescope' the objective was mounted on a tower or pole and controlled by cords, while the detached eyepiece was mounted near the observer. Needless to say this modification proved equally inconvenient and encouraged the rapid transition to reflecting instruments. Metal tubes occur first in reflecting telescopes, where the sliding action is not essential; for refractors and all compound microscopes they are common only after *c* 1750, the tubes being formed from rolled sheet. Drawn metal tubing was not available until nearly a century later.

Having now considered the optical parts and their mounting in the main body of the instrument, it is important to draw attention to the part played by the stand and accessories that supported the tube, provided for focusing, and enabled the instrument to be suitably directed. In telescopes and microscopes this was generally the weakest part of the design, and the cause of many of the troubles that must have occurred in use. Early compound-microscope bodies were often supported by a long weak arm fixed near the objective, or by a loose, coarse screw; the slightest movement of the eyepiece would have the effect of sending the object out of focus and displacing it in the field (figure 372). An improved version made by Edmund Culpeper (1660–1738) and his associates mounted the body firmly on a tripod stand, thus securing much better stability. Later instruments reverted to the old arrangement of pillar-support, though towards the end of the eighteenth century more attention was paid to securing mechanical stability.

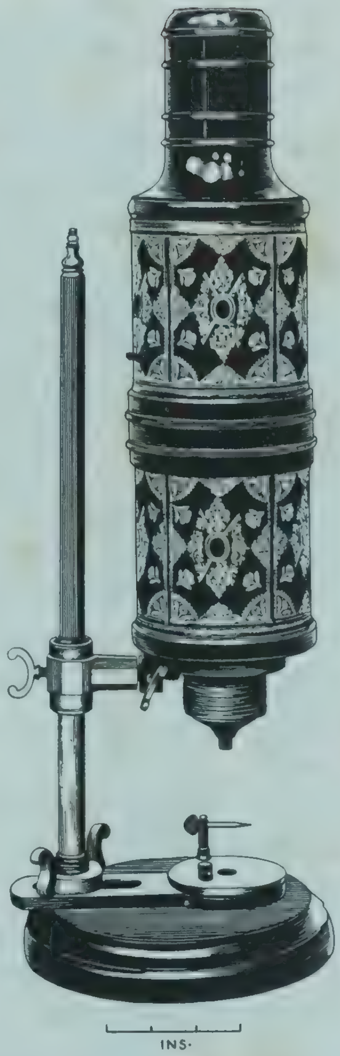


FIGURE 372—*Microscope made for Robert Hooke by Christopher Cock* (c 1660). *The objective is mounted in a cell at the bottom of the body, which also contains an eye-lens and a field-lens. The body slides on the pillar, and screws up and down in the brass arm for fine adjustment.*

VI. OTHER NEW INSTRUMENTS

From about 1650 onwards, when the new optical instruments were coming into vogue, there was a corresponding decline in the popularity of traditional instruments. The astrolabe was practically obsolescent by the beginning of the seventeenth century, the plain quadrant lasted for another few decades, and the enormous flow of sun-dials of all shapes and sizes steadily lessened until they were ousted by the pendulum-clock and pocket-watch during the second half of the eighteenth century. Skill in dividing and engraving metal plates ceased to be the central feature of the instrument-maker's craft but remained at a high level. New forms of practitioners' instruments were constantly being made, such as the circumferentor (full circle) and the graphometer (semicircle) used in surveying, the back-staff and the reflecting octant for navigation, and the cases of divided rules and drawing-instruments used by draughtsmen and gaugers. These were augmented by newer devices such as the theodolite and the bubble-level, and improved by the introduction of telescopic sights in place of open pinnules. The old techniques were also applied to instruments for calculation, amongst them Napier's bones, the sector (figure 367), and various logarithmic and other scales.

The physical instruments popularized by the investigations of the learned academies posed quite new problems of instrument-making. The Florentine glass-blowers who had made the first sealed alcohol thermometers for the Accadèmia del Cimento, *c* 1660, were far superior in their techniques to any rivals elsewhere in Europe—surviving instruments show, for example, the degree-markings made by fusing little spheres of black glass to the main tube at closely regular intervals (figure 373). Mercury barometers were perhaps more simple to construct since they did not involve the sealing of a filled tube, but it was not until long after the experiments of Torricelli in 1643 that the barometer and the thermometer came into popular use. Technically, the early history of both instruments belongs to the craft of the glass-blower until late in the seventeenth century, when barometer- and thermometer-tubes were mounted with engraved scales, cursors, and other fittings, so becoming part of the commerce of the instrument-maker.

The history of the pneumatic pump is interesting, not only for the large part it played in science by drawing attention to the physical properties of 'airs', but because it was the first large and complex machine to come into the laboratory. The old astronomical instruments had sometimes been made of great size, and, as has been remarked, the refracting aerial telescopes (p 635) attained stupendous lengths, but in the vacuum pump for the first time there was complexity as well as size and engineering began to invade the province of precision instruments. The first experiments of Otto von Guericke had been described by Schott in 1657, and were quickly seized upon and improved by Boyle, Huygens, Papin, and others. Shortly after the beginning of the eighteenth century, one of the first mechanics of instrument-making, Francis Hauksbee (1687–1763), began to make vacuum pumps in quantity, and to a design that remained essentially the same for about 150 years (plate 27 A). The technical methods developed by such mechanicians stand at the beginning of the direct line of evolution leading to the steam-engine and the internal combustion engine. Although these pumps were made and sold by people calling themselves instrument-makers there is little in common between the techniques they required and those in general use among the makers of other instruments.

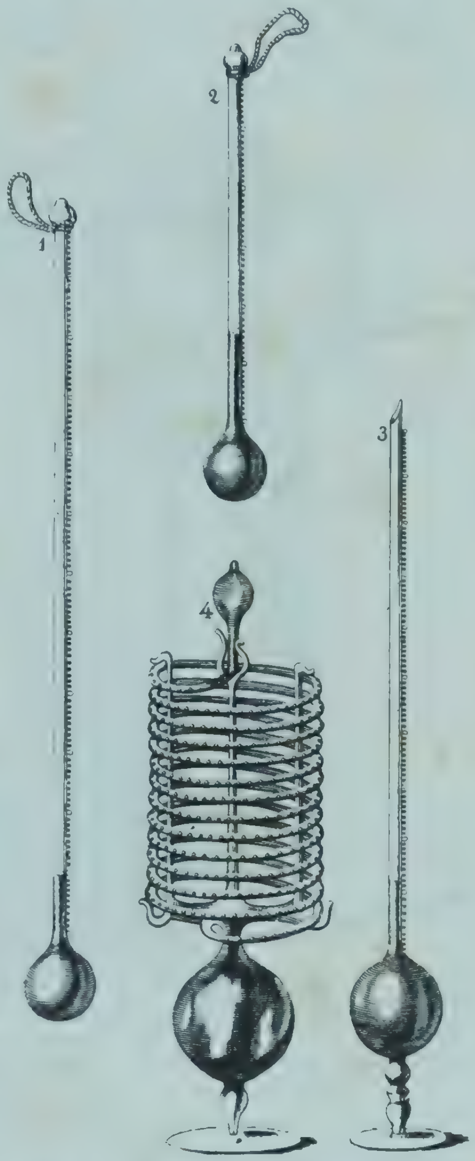


FIGURE 373—*Thermometers designed by the Accadèmia del Cimento* (c 1660). *They are graduated by small spheres of coloured glass fused to the tubes. No. 4 is a spiral thermometer with a very long scale.*

Nearer the main stream of development in techniques of instrument-making were the devices made popular by the increased interest in magnetic and electrical phenomena towards the end of the seventeenth century and the beginning of the eighteenth. Hopes of a solution to the problem of determining longitude at sea led to a demand for devices to measure more accurately the magnetic variation and dip, and early in the eighteenth century the general interest in magnetism led some instrument-makers to sell neatly mounted lodestones, miniature compasses, and magnets of all shapes and sizes designed for the pleasure and edification of the amateur. By this time magnetic compasses, often mounted on crude but effective gimbals, had long been standard equipment on board ship, and there were many specialist compass-makers working in the shipyards or for naval departments. The electrical machine, however, followed a different course, being, like the air-pump, an instrument of large size though not involving such precision in engineering. During the eighteenth century electrical machines became ever larger, and numerous complex modifications were introduced in order to produce more striking effects (figure 374). If the air-pump can be considered as leading to the steam-engine, the electrical machine stands at the beginning of the chain leading to the great machines of modern physics—the electrostatic accelerator, the cyclotron, and the other instruments that are now almost institutions in their own right.

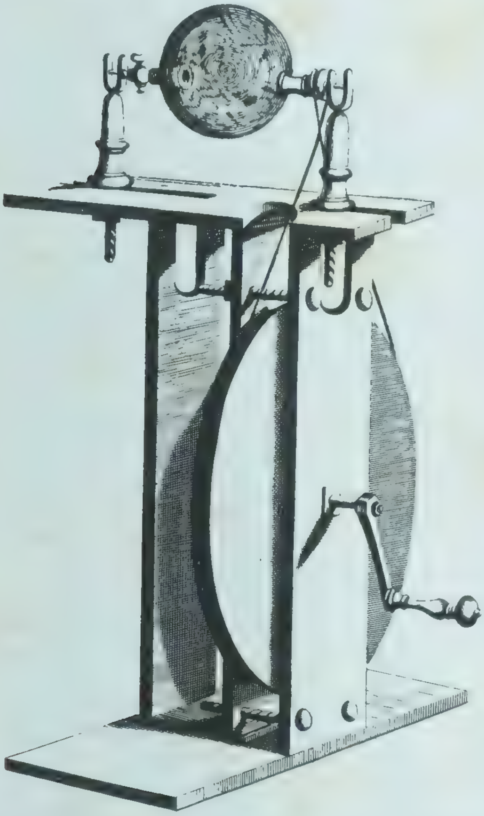


Figure 374—*Electrical machine made by Francis Hauksbee, senior,* c *1709. The figure shows the luminous effects produced inside an exhausted glass sphere when it is electrified by friction against the hand.*

Shortly after 1700 a new market for instrument-making began to appear. Before then, the majority of instruments had been made for the practical man or for use by pioneering scientists and amateurs. The front line of research was now beginning to recede from the understanding of the amateur and novice, but increased popular attention to science, with little emphasis on mathematics and scientific pedagogy, led to a demand for new types of apparatus suitable for demonstrative experiment. Even during the Middle Ages some teaching devices—such as the demonstration armillary sphere (p 613)—had existed, but now the more popular craftsmen began to sell attractive cases containing sets of apparatus to demonstrate the laws of mechanics or magnetism, boxes of models to illustrate solid geometry, sets of slides and objects for the beginner's microscope, pairs of globes, and such complicated instructional devices as the orrery—an excellent example of the craft of the clock-maker carried into the range of non-horological instruments (plate 27 B). This tendency became more and more marked as the century proceeded (p 642).

VII. THE QUEST FOR ACCURACY

It has been shown how the making of precision instruments was transformed during the scientific revolution by the making of new devices—some instruments merely employing new adaptations of old principles, better fitted for specific practical uses, others embodying quite new scientific principles. Besides these changes there was a drastic and far-reaching transition in the attitude towards precision and the means of attaining it. New experiments and new measurements

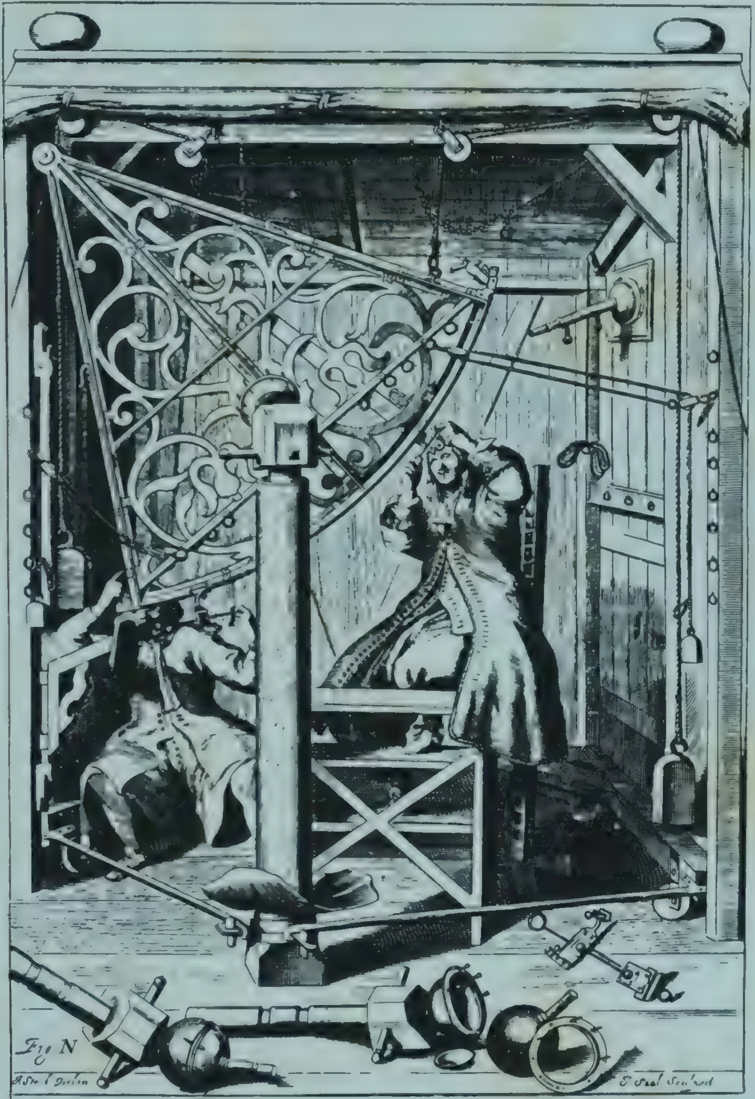


FIGURE 375—*View of part of an observatory (1673) showing the mounting of a large sextant used to measure the angular separation of celestial bodies. Note the counterbalancing weights to relieve strains; the screw-adjusted sights (similar to the adjustment in figure 370); the need for two observers.*

constitute only part of the scientist's activity; carrying old measurements to a further place of decimals may be at least as important. Nowhere is this more evident than in astronomy. The work of Kepler (1571–1630) had shown clearly the advantage to be gained by precise knowledge of small fluctuations and secular motions. He had depended on the observations made by Tycho Brahe at the end of the sixteenth century, and the instruments used had pushed accuracy to the limit obtainable by the naked eye. Three main problems are involved in astronomical angle-measuring devices: (*a*) the accurate sighting of the star or other object; (*b*) the accurate alignment and division of the graduated circles; and (*c*) the accurate reading of the graduations. To all of these Tycho Brahe and others, such as the Danzig astronomer Hevelius (1611–87), directed their attention. Special pinnule-sights were designed to avoid parallax and to use the full resolving power of the eye; the instruments were made as large as possible and provided with counterbalancing weights so as to minimize distortion by bending under gravity (figure 375); scales were provided with the nonius or diagonal-scale device (figure 376) which, like the vernier later introduced, enabled subdivisions of a degree to be estimated accurately without the labour of engraving them to a high degree of fineness all over the limb of the instrument.

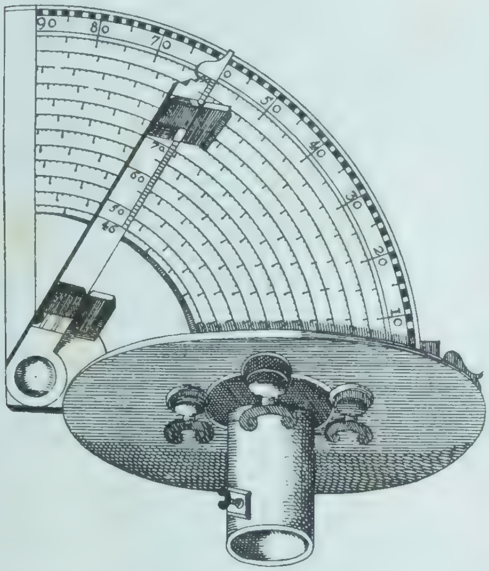


FIGURE 376—*Dudley's quadrant with a nonius for reading parts of a degree (1646). Each graduated arc is divided into a different number of parts, e.g. 90, 89, 88. . . . Observing that the alidade falls on the* m*th part of an arc divided into* p *parts, the angle is found to be 90* m/p *degrees.*

It is ironic that fate should have allowed Brahe and Hevelius to exercise all their powers in seeking the limit of accuracy of the naked eye when their work was to be followed so closely by the invention of the telescope, which made possible an enormous increase in accuracy with much less trouble. The telescope appears to have been used in taking astronomical measurements (as distinct from qualitative observations) within a few decades of its invention, and William Gascoigne had made a micrometer fitting on an eye-piece as early as 1640; but the general replacement of open sights by telescopic ones did not occur until after 1665. At that time Robert Hooke constructed a number of telescopic measuring-devices, and thenceforward very few observations with open sights were made by astronomers. Yet it was not until the mid-eighteenth century that the telescope became common as a component of surveying- and navigating-instruments.

The former limiting factor in the attainment of accuracy having been removed, some attention was next paid to other considerations in instrument-design. In the construction of the body of the instrument it was essential to obtain a greater degree of mechanical precision, and here again (as with the vacuum-pump) instrument-makers were called upon to produce work that would now fall into the province of the precision engineer. Much attention in particular was paid to the construction of accurately centred and true-running bearings and pivots, and divided limbs were carefully designed with cross-strut supports to prevent deformation (figure 377). When all this had been done it rapidly became apparent that the chief remaining limitation lay in the method of dividing and reading the scale itself.

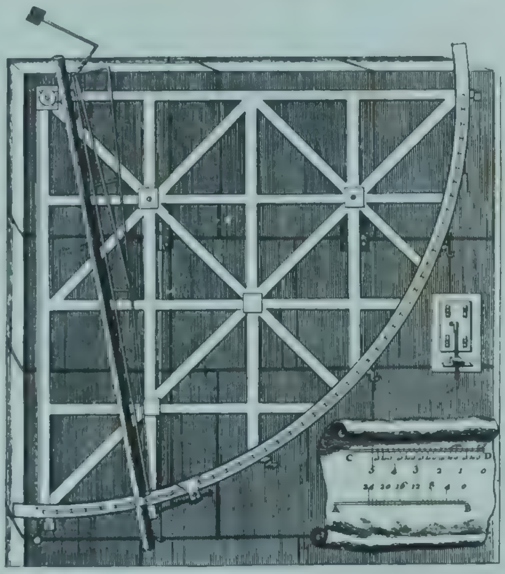


FIGURE 377—*Five-foot mural quadrant of copper, with telescopic sights, made by George Graham (1742).*

The first steps in mechanical subdivision had already been made by clockmakers, who used a specially marked wheel for laying out the position of teeth on gear-wheels. This method relied on a previous geometrical division of the marked wheel, and it was not until *c* 1760 that the first steps were taken by the Duc de Chaulnes (1714–69) in France and by Jesse Ramsden (1735–1800) in England towards a completely mechanical original division of the circle (figure 378). By about 1780 the type of device due to Ramsden had swept the board and was in general use, not only for circular arcs but for the division of linear scales of high accuracy when these were required. In essence, Ramsden's dividing engine was a simple enough application of the worm-and-wheel principle that had been used long before, even on Hero's dioptra (p 609), but the mechanical execution of this principle was so exacting that it opened up a new era in precision workmanship and a new concept of instrumental accuracy. Thenceforward the technological problems of instrument-making have been a determining factor in the progress of scientific research, each advance in instruments allowing the scientist to measure to a higher degree of accuracy, and each advance in science posing fresh problems for the ingenuity and precision of the instrument-maker. Although astronomy was the first science to profit from the removal of the old limitations, the process was rapidly extended to other fields. For example, stress was now laid on accurate time-measurement, and clock-driven telescopes began to be widely used in the increasing number of observatories. The observatories themselves exercised a considerable influence on instrument-design since they were perhaps the largest customers for the more complex and expensive devices that acted as prototypes for other products of the artisans. Ramsden's dividing-engines were not only used for astronomical instruments but also for the scales of navigation- and surveying-devices.

During the latter half of the eighteenth century, indeed, instrument-making expanded in scope from fine engraving to take in many quite different techniques needed to produce the new optical and physical instruments invented during the scientific revolution. There had also been an internal revolution, which led to a new approach to the problems of precision workmanship and to the appearance of a new class of artisans whose skill in precision engineering was vital to the progress of science (figure 379).

VIII. FROM INSTRUMENTS TO APPARATUS

In the century following the death of Newton in 1727 there was an increasing acceleration in the growth of the scientific movement and of its importance in national life. At the same time, the research front was steadily advancing, producing more and more exciting knowledge and understanding of the world, but becoming less and less easy for the non-specialist to comprehend. It has already been remarked that this created some demand for those products of the instrument maker which were designed for demonstration and instruction rather than for research or for use by the practitioners of survey, gunnery, and navigation. During the century this type of instrument-making developed so considerably that it began to exercise a major influence on the craft and on the techniques needed by its artisans. The change is, in fact, more important than might be thought, for at the beginning of the modern period, when public laboratories were coming into being, the demand was largely for apparatus for instruction and the performance of routine experiments rather than for instruments needed for original research. Already during the latter part of the eighteenth century it was becoming apparent that the new devices needed by the active scientist had to be specially built for him by an instrument-maker working to his order, perhaps using sundry components and portions of instruments which were standard products of the trade.

There was a tendency, therefore, for the better and more versatile artisans to

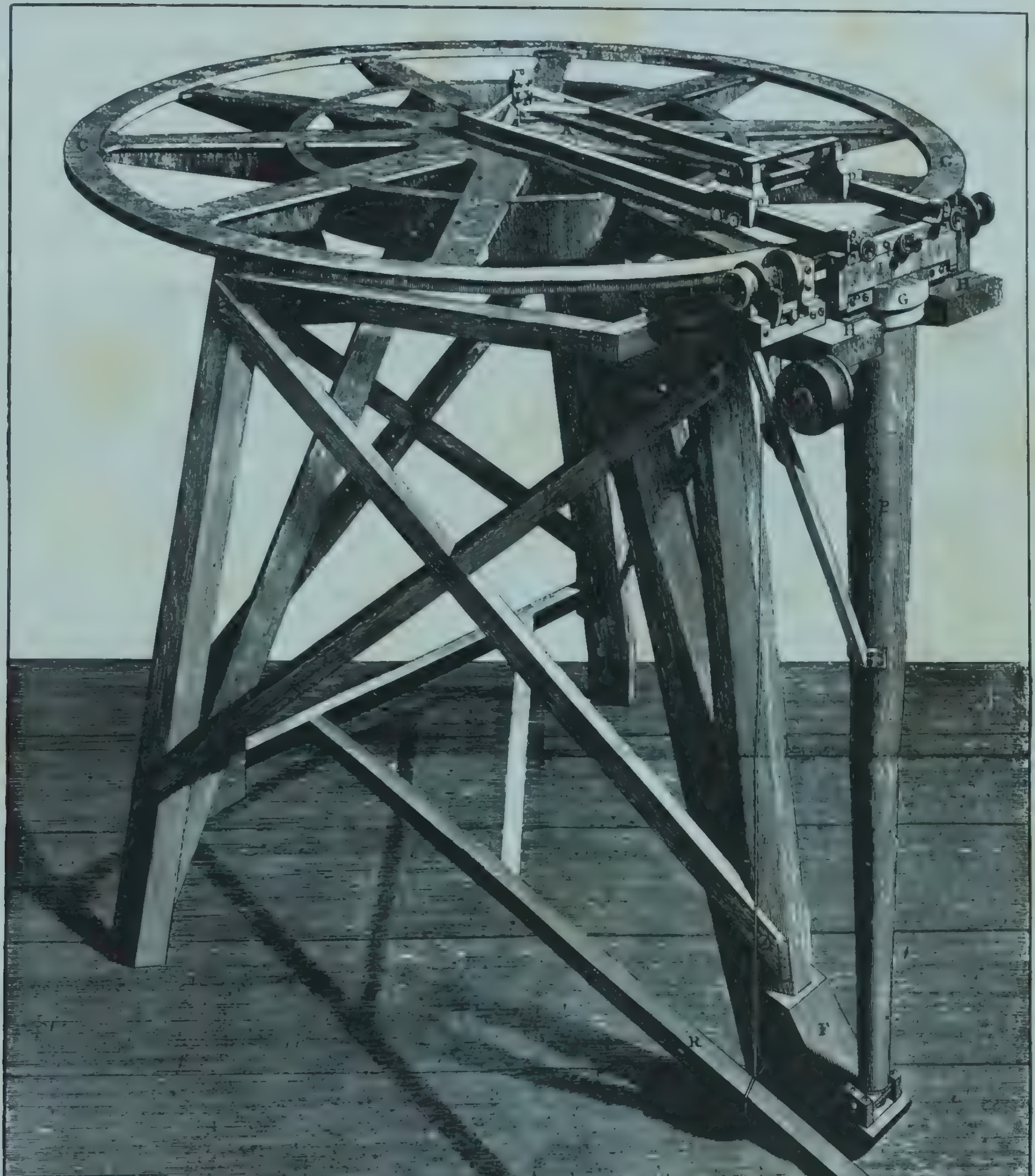


FIGURE 378—*Ramsden's circular dividing-engine* (1777). *The plate to be divided is screwed to the large toothed circle* (CC). *The scriber is fitted to the sliding carriage* (DD). *The circle is turned through a determined arc by depressing the treadle* (R) *which by means of a cord and a ratchet-device rotates the shaft carrying a worm (seen above* (Q)) *meshing with the circle. A mark of the scriber following each operation of the treadle produces a series of scratches on the plate at exact intervals.*

be employed in constructing instruments specially designed for a particular piece of work by one scientist, and there was also a move towards the manufacture of standard components and apparatus capable of being applied to several different experimental purposes rather than to one single and definite use. Thus we find lenses and prisms separately mounted so that they can be combined as required; there are reading-micrometers, pressure-gauges, and other measuring-instruments that can be used only in conjunction with other pieces of apparatus; there are Leyden jars, dischargers, spark-apparatus, and other apparatus for use with the electrical machine.

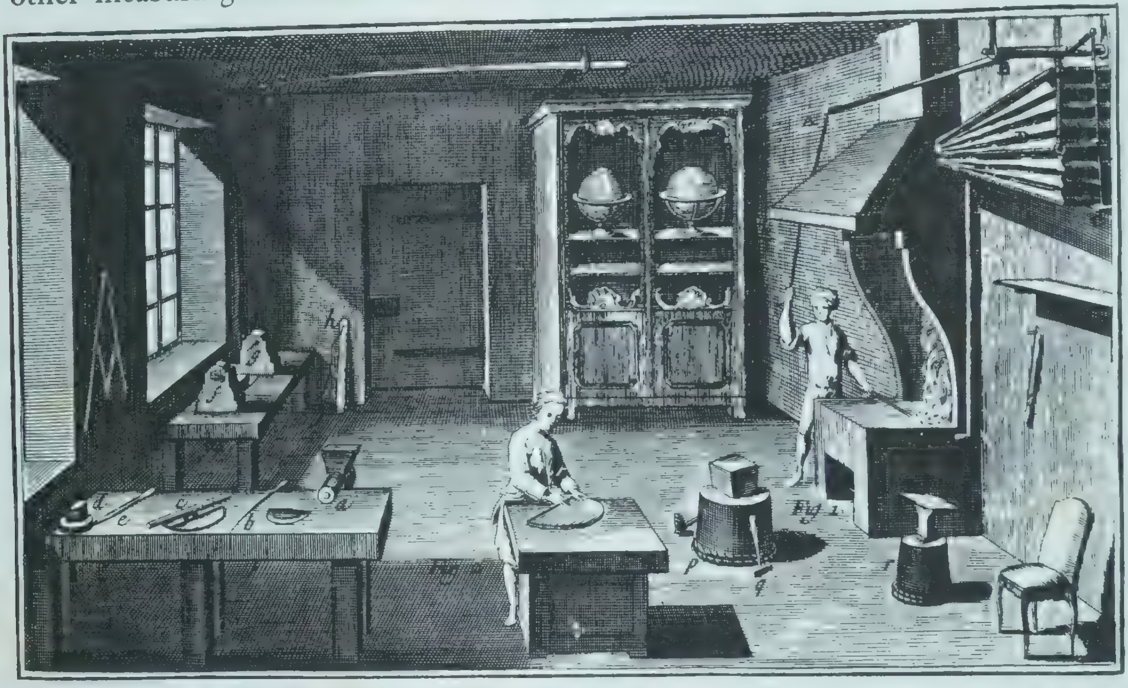


FIGURE 379—*Workshop of an eighteenth-century mathematical instrument-maker.* (Left) *Pole-lathe;* (centre) *work-bench and stone;* (right) *forge and anvils.*

In addition to making components capable of being variously combined in apparatus for research, the instrument-makers continued to produce an increasing range of instruments for teaching and demonstration. Because the work of Newton had emphasized the fundamental position of mechanics in natural philosophy, many of these instruments were intended to elucidate mechanical principles, such as the laws of force in their static and dynamic aspects, and the laws of impact (figures 380, 381). These demonstration devices were frequently built on a large scale, and many were masterpieces of the work of the cabinet-maker and joiner as well as of the mechanic; they were made like pieces of domestic furniture and ornamented in the style of the period. Many of the best-known instrument-makers of the age specialized in, and were widely famed for, their instructional apparatus, and the books they wrote to explain the use of their wares did much to popularize science and lay the foundations of the teaching of science outside the universities. George Adams (d 1773), perhaps the best instrument-maker of his day, wrote books of this sort that went through many editions and must have figured in the basic education of a large number of nineteenth-century scientists. His instruments were equally popular, and in a large collection made for George III many of them are still preserved (plate 27 A).

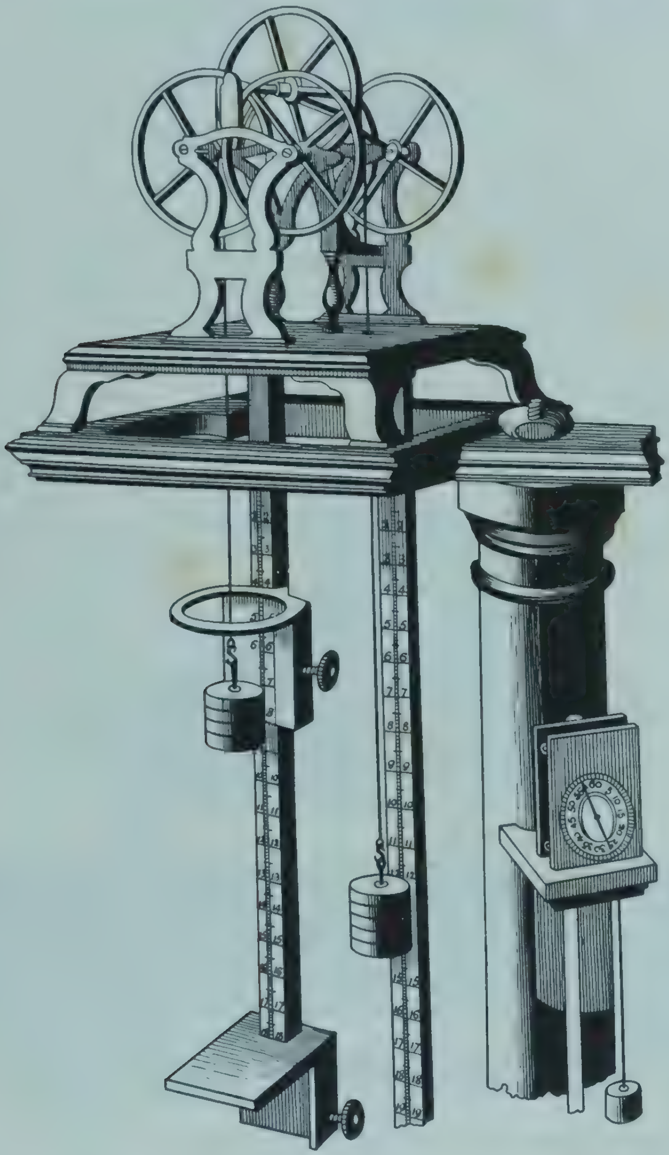


FIGURE 380—*Atwood's machine for demonstrating Newton's law of gravitation.*

By the time of Adams the craft of the instrument-maker was far removed from that of the early artisans with their astrolabes and sun-dials. The industry now produced standard instruments for the practitioners, standard components and apparatus specially designed for research, and all the furniture of the scientific school-room. From being principally a group of engravers the makers had joined hands with several other specialist technicians to manufacture optical, pneumatic, magnetic, and electrical devices involving quite new principles of scientific design and mechanical construction.

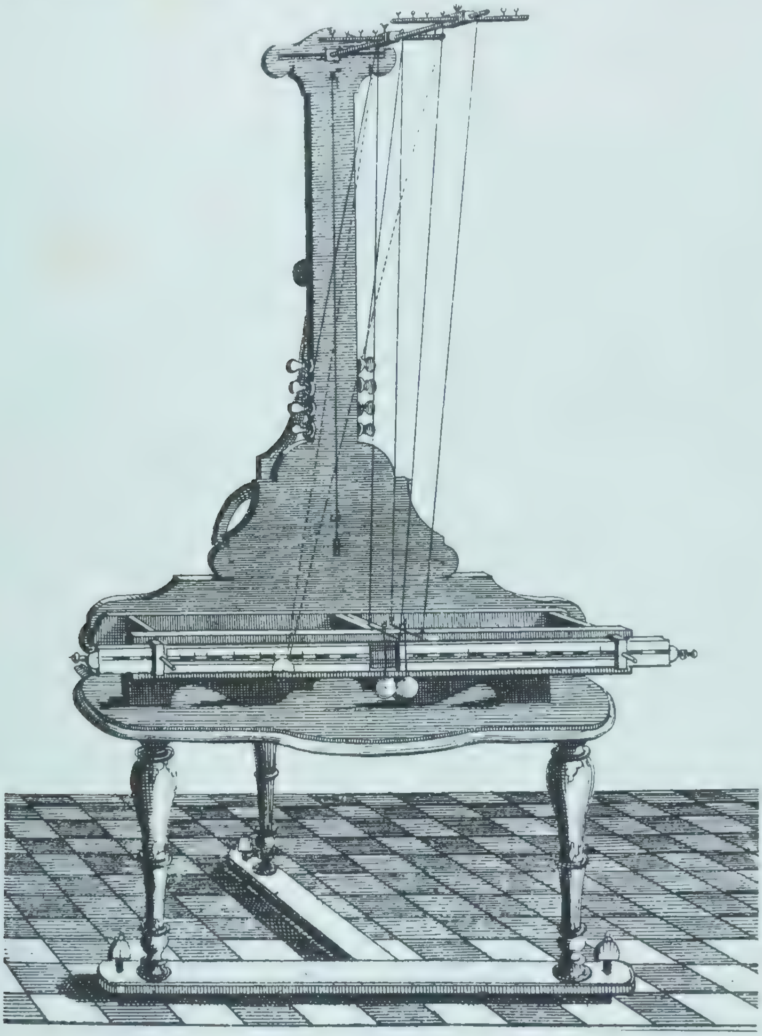


FIGURE 381—*Apparatus for making experiments on the impact of bodies, c 1750.*

Most important of all, the quest for accuracy had led them to produce apparatus of large size and of the finest engineering precision, and had forced them to pay special attention to all means of increasing this precision. Such instrument-makers provided the scientist with the tools for his experiments, so that he became increasingly a laboratory worker surrounded by apparatus, a picture quite characteristic by the beginning of the nineteenth century. Scientific instrument-making, moreover, had made its noteworthy contribution to the industrial revolution that was then well under way, as well as to science, for the trend towards precision engineering rendered it natural for great engineers like John Smeaton (1724–92) and James Watt (1736–1819) to learn the elements of their trade in the ranks of the instrument-makers. The steam-engine, the theodolite, the sextant, the planetarium, and the radio-telescope are all descendants of the line starting with medieval astrolabes and sun-dials.

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24

MECHANICAL TIMEKEEPERS

H. ALAN LLOYD

I. THE EARLIEST MECHANICAL CLOCKS

MECHANICAL clocks were first devised in the thirteenth century. They were designed for controlling the force of a falling weight and, in the fifteenth century, the recoil of a spring, so that they should act slowly and regularly upon a suitable indicator. A very early device (reconstructed in figure 382), perhaps copied from one yet older, appears in the *Libros del Saber Astronomia* [1]. This book was compiled by a group of scholars in 1276–7 for Alfonso the Wise of Castile, a great patron of learning. A weight was attached to a cord wound round a drum; as it fell the speed of rotation of the drum was controlled by mercury in an annular container fixed within it. The drum in turning raised the mercury until it counterbalanced the driving-weight, which could then fall only slowly as the mercury trickled through holes in partitions preventing its free flow in the container. Thus the rate of revolution of the drum depended on the viscosity of the mercury and the size of the holes, and was almost uniform. This controlled slow motion was continuous until the cord was fully unwound.

In all later clocks it was found preferable to interrupt the action of the driving-force regularly and periodically, so that the indicator moved in steps rather than continuously. This is the function of the *escapement*, which periodically checks and releases the driving-train. The accuracy of the clock then depends on the regularity of the escapement's action. The first great step towards modern time-measurement was taken in the later thirteenth century, in the use of an escapement deriving its own motion from the fall of a weight, to control the rate of fall.

Once regulation of the descent of a weight had been achieved, the motion thus obtained could be applied to a variety of purposes—to the rotation of the rete or star-map of an astrolabe (p 604), to the striking of bells at regular intervals, or to the movement of hands over a dial-face. The first record in Europe of a device controlled by an escapement is in the sketch-book of the French architect, Villard de Honnecourt (*c* 1250–*c* 1300) [2]. His drawings were largely of things that he saw in his travels, so that it is unlikely that he himself invented this

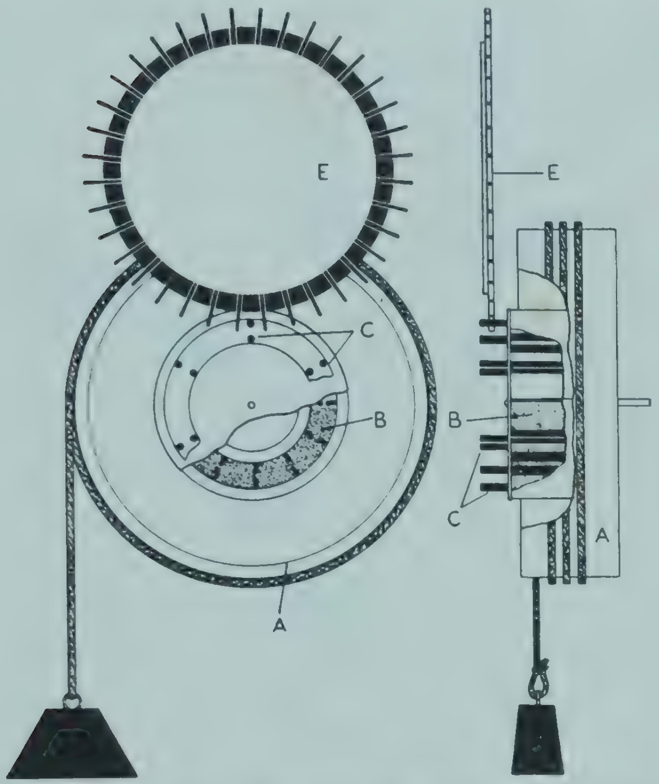

Figure 382—*Alfonso X's mercury clock.* A, *the weight-driven drum;* B, *the mercury container divided by perforated partitions;* C, *the studs turning the dial* E.

mechanism (figure 383). No explanation is given, but beneath the sketch is the legend: 'How to make an Angel point with his finger towards the Sun.' This suggests that the figure was intended to revolve once in twenty-four hours. The angel would be mounted on the vertical shaft.

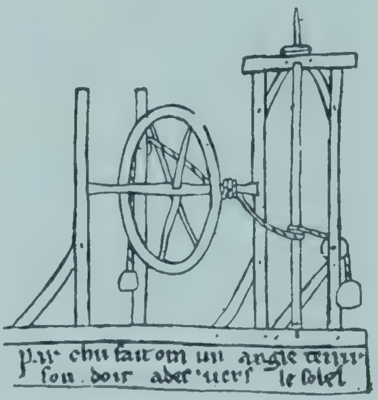
p.ii· chu fait om un angle tenir
ſon doit ades·vers le solel

Figure 383—*Villard de Honnecourt's rope-escapement.*

In this sketch of Villard—of what can hardly be called a clock—the descent of the weight and the uniform rotation of the shaft are regulated by to-and-fro oscillation of the wheel round whose axle the driving-cord is wound. The period of the wheel's oscillation is determined by many factors, including its moment of inertia, its friction on its bearings, and the force acting on the cord. Until the seventeenth century all clocks were similarly controlled by the oscillation of a heavy mass, in the form either of a wheel (as here) or of a pair of weighted arms. Although the escapement was vastly improved, such clocks all had the same defect, namely that the period of oscillation, and hence of the interruption of the action of the driving-force, varied with these factors, which themselves were liable to change. In other words, such escapement mechanisms did not constitute a periodic system whose frequency is independent of these variables.

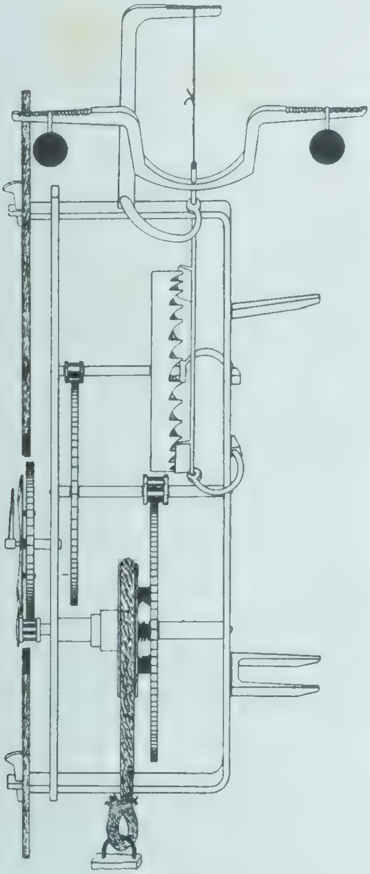

FIGURE 384—*A fifteenth-century mechanical clock in its simplest form. The balance is a notched cross-bar, or foliot, with two small cursor weights. Regulation was primarily by the size of the weight employed, with a fine adjustment by means of the cursor weights. The verge-arbor is suspended from a notched arm by a thread, affording another means of regulation by varying the angle of impact between the pallet and the tooth of the crown-wheel. Inclining the pallet towards the teeth of the crown-wheel ensured a longer period of contact, hence slower going, and vice versa.*

The earliest escapement, controlling the fall of a weight, is known as the verge.[1] In its simplest form it effects the regular interruption of the rotation of a crown-wheel, caused by a descending weight (figure 384). Projections from the rod or verge, called pallets, engage alternately with teeth on opposite sides of this wheel. The verge is pivoted to permit its oscillation and has attached to it at right-angles a balance-rod with an equal weight at each end. As the crown-wheel rotates, the swing of the balance-rod in one direction is first stopped and then reversed, so that it swings back in the opposite direction. Next, as the engaged tooth of the crown-wheel is released from the relevant pallet, the other pallet engages with a tooth on the other side of the wheel, reversing the swing of the balance once more, and so on. The speed of the intermittent rotation of the crown-wheel is therefore dependent on (*a*) the force applied to it by a spring or falling weight through the gearing, (*b*) the friction in the train and escapement, and (*c*) the moment of inertia of the balance. The escapement, linked by gears both to the driving-barrel and to the indicators or hands, forms the *going-train* of the clock.

If a clock is to strike the hours it must also have a *striking-train*, usually driven by a separate weight or spring, which is released at intervals by the motion of the going-train. The date of the invention of the striking-train is uncertain. The oldest surviving clock striking the hours in sequence is in Salisbury

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[1] Probably derived from the Latin *virga*, a wand or rod.

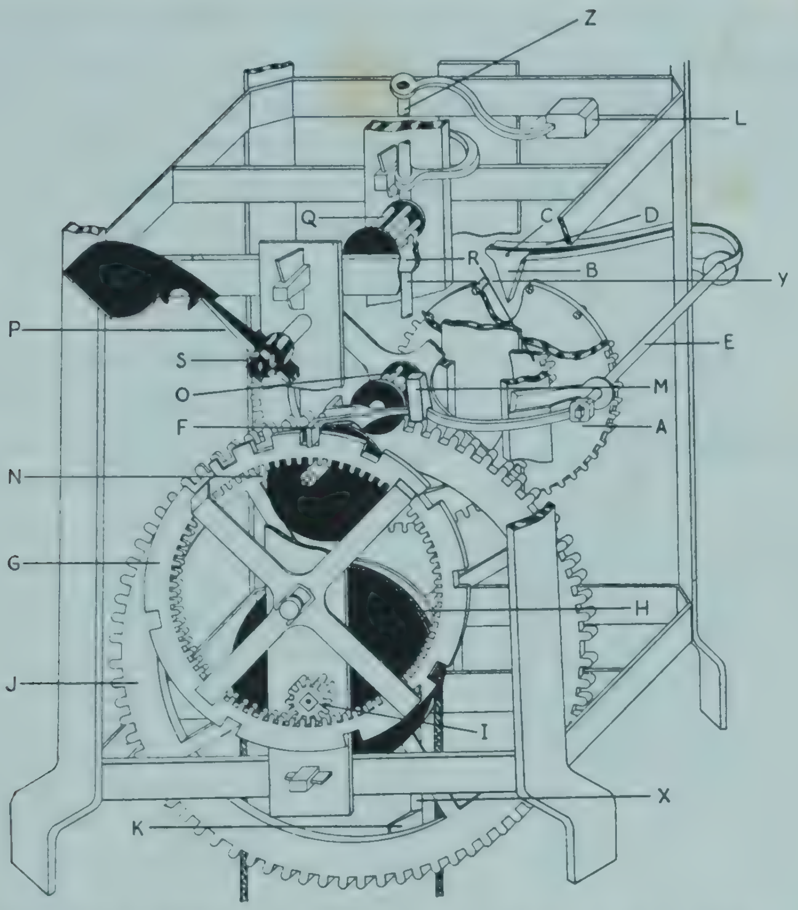

FIGURE 385—*Early form of simple striking-train,* c 1550. *Once an hour one of the twelve pins on a plate fixed to the hour-wheel* (A) *carried by the front plate raises the triangular piece* (B), *which is pivoted at* C *and has a restoring spring* (D). B *by means of the arbor* (E) *raises the locking-piece* (F) *out of the groove in the locking-plate* (G) *and another out of the slot in the eccentric cam* (N). *The striking-train is now free to revolve, impelled by a weight* (not shown) *attached to a cord passing over the grooved wheel* (H). *The pinion* (I) *on the arbor of* H *turns the locking-plate* (G). *Twelve pins* (not seen) *at equal intervals on the far side of the great wheel* (J) *catch the pallet* (K) *at the base of the arbor* (XYZ) *carrying the hammer* (L), *which, through a restoring spring* (not seen), *strikes the bell* (not shown). *The locking-piece having dropped upon the rim of the locking-plate because of the weight* (M), *the eccentric cam* (N), *driven by the great wheel* (J) *through the pinion* (O), *raises the locking-piece again. The next pin on* J *then catches* K *which strikes again, and so until the locking-piece falls into a notch in the locking-plate and a second locking-piece into the notch in the cam. The notches in the locking-plate are so spaced that the hammer may strike one to twelve successively.*

To retard the fall of the weight, a fan (P) *is geared through the pinions* (O, Q) *and the wheel* (R), *to revolve at a high speed. Attached to the unseen arm of the fan is a click which engages with the ratchet* (S) *allowing rotation in one direction only. Variations in the design of striking-trains, notably the provision of a 'warning period' of two or three minutes before the strike, when the fan is held fast, are common. In France the locking-plate system is still widely used; elsewhere it is applied only to turret-clocks. It cannot be used to provide a repeating-action.*

Cathedral and is of 1386. This, however, has been so modified that it is better to illustrate the Dover Castle clock, which still preserves its original foliot (or verge) escapement (plate 32 A).

In early striking-clocks a wheel, notched at progressive intervals, controls the number of strokes on the bell while revolving blades form an air-brake, limiting the speed of striking (figure 385). This was the only form of striking-mechanism known until 1676 (p 669). The earliest mechanical clocks were probably designed merely to strike bells, warning a monastic officer to announce the appropriate ritual, and they then probably did not indicate time visually. A striking-train, however, would have been meaningless unless a going-train, including the escapement, were available.

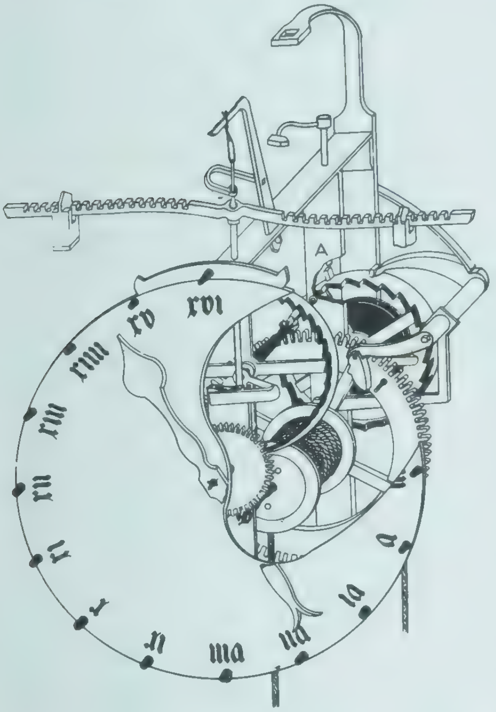

FIGURE 386—*Early monastic alarm clock, c 1390, recording the hours of darkness to a maximum of sixteen. The stop* (A) *on the alarm crown-wheel, stopping and re-setting the alarm after one revolution, is an improvement on the design of earlier clocks.*

There is at Nuremberg an alarm clock of 1380–1400 (figure 386) which has sixteen knobs indicating the time by touch in the dark. It has also a pinion of three leaves driving a wheel of 48 teeth completing one revolution in sixteen hours, thus confirming that the clock was designed for night use only. Until the early seventeenth century, at Nuremberg and in other places, time was reckoned by hours of daylight and darkness, about eight of daylight to sixteen of darkness at midwinter with the reverse ratio at midsummer. The sexton would set the clock each night at the first hour of darkness. Once an hour a lifting device would release the second crown-wheel, that of the alarm, and this, set in motion by its own driving-weight, would oscillate its own verge-staff pallets. At the end of the verge-staff, on the curved arm, is carried a hammer striking the bell (not shown). On the alarm-wheel is a stud which stopped it after one revolution and reset the alarm. This arrest of the alarm is something new, and eliminated the necessity for rewinding the alarm after each release. From now on the awakening function of the sexton was increasingly replaced by the automatic sounding of a bell, sometimes struck by a mechanical figure or *jaquemart*,[1] whence our English clock-jack. The word 'jack' has been applied to many mechanical devices, such as roasting-jack, screw-jack, and so on.

Quarter-striking was the next development, which is exhibited earliest in the great clock at Rouen of 1389. A third train was introduced to provide for this addition, on the same lines as the hour-strike, but with the locking-plate having four divisions only instead of twelve. A quarters bell would be struck 1, 2, 3, and 4 times and, after the last, the hour on its own bell.

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[1] That is, Jack (Jacquème) with a hammer (*marteau*).

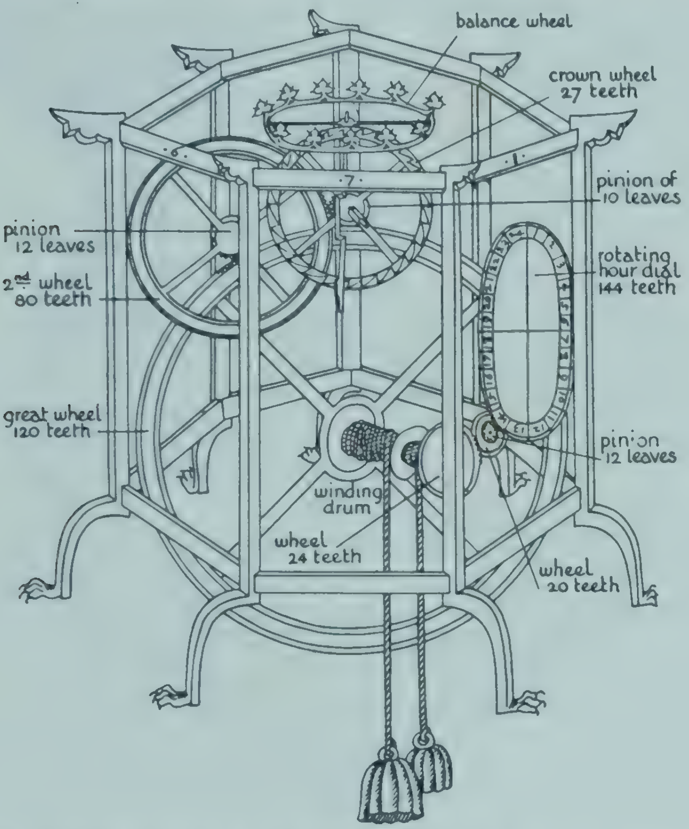

FIGURE 387—*Dondi's incomplete sketch of his going-train, 1364. It contrasts with the very precise details given for other dials and trains. The clock has a verge-escapement fitted with a balance, but no striking-train; it embodies the early practice of combining a fixed hand with a revolving 24-hour dial. As the numbers of teeth shown on the sketch indicate, the winding-drum makes 10 revolutions in a day; the second wheel, therefore, revolves 100 times a day, and the escape-wheel 800 times. Since each revolution occasions 54 oscillations of the balance (1800 in an hour) the balance has a 2-second beat—the standard of Dondi's time. The pinion meshing with the hour-circle was made to slide to allow for daily adjustment. This was essential when, as in Italy where this clock was made, the 24-hour day was reckoned as starting at sunset.*

II. THE FIRST ASTRONOMICAL CLOCK

At a very early date there were attempts to embody the celestial motions in clocks; indeed, the ambition to do this seems to have played a large part in the evolution of uniformly rotating mechanisms. An astronomical clock was first developed in medieval Europe by Giovanni de' Dondi between 1348 and 1362. He constructed a most complete clock (figure 387), which set out the motions of the Sun, Moon, and five planets with surprising accuracy, and included a perpetual calendar for the movable feasts of the church. Dondi left a full description, both of the clock and of his method of construction. He made it with his own hands, entirely of bronze, brass, and copper, an operation that took sixteen years. Because of the astronomical complexities much greater force was required to drive the going-train of Dondi's clock during the night than during the day. He met this difficulty with great mechanical ingenuity, introducing an auxiliary driving-weight to provide for the extra strain imposed on the going-train when six of the seven planetary dials received their nightly advance at the same time from the drive incorporated in the annular calendar wheel of 365 teeth.

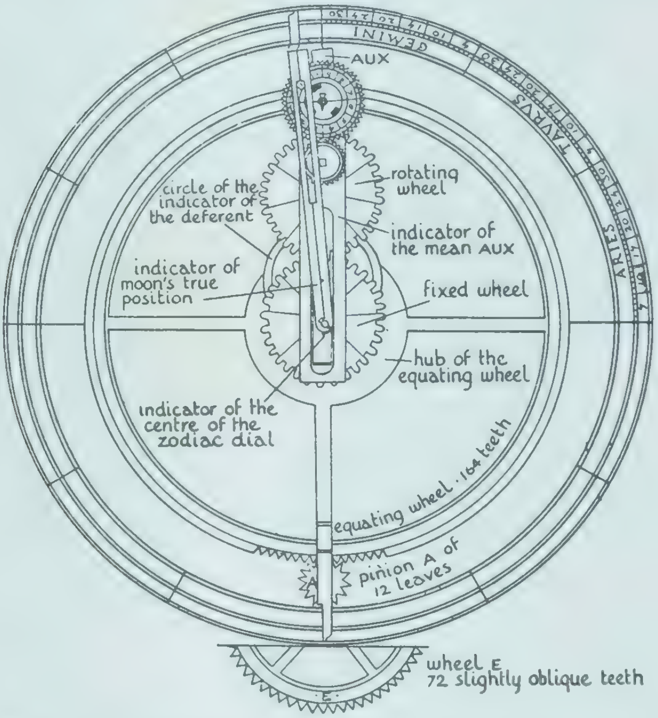
GEMINI
TAURUS
ARIES
AUX
rotating wheel
circle of the indicator of the deferent
indicator of the mean AUX
indicator of moon's true position
fixed wheel
hub of the equating wheel
indicator of the centre of the zodiac dial
equating wheel. 164 teeth
pinion A of 12 leaves
A
wheel E 72 slightly oblique teeth
E

FIGURE 388—*Dondi's lunar train. Note the oval wheels with irregularly spaced teeth, the outer revolving around the fixed inner wheel.*

In order to cut 365 (5 × 73) teeth on one of his wheels, Dondi divides the whole circumference into 6 parts, from which he obtains 1/18th and from this 1/72nd. He then divides the remaining 71/72nds of the circumference into 72 parts, thus obtaining 73 nearly equal parts, which he further divides by 5.

To explain Dondi's perpetual calendar for the movable feasts of the church would lead us too far afield, but it may justly be said that he solved the problem mechanically better than any of his successors for 400 years. His ideas were beyond his contemporaries and immediate successors and hardly affected them.

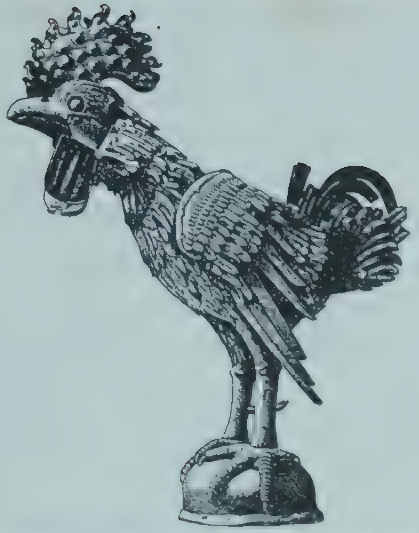

FIGURE 389—*The mechanical cock made for the first Strasbourg clock in 1354. It is of wrought iron, with copper comb and beard, mounted on a wooden base.*

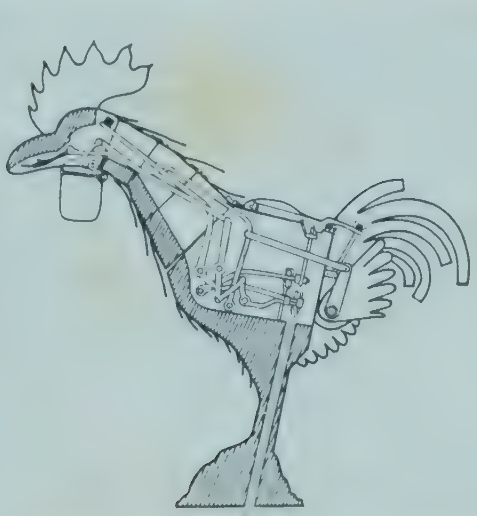

FIGURE 390—*Diagram showing the mechanism for the articulation of the head, beak, and tongue. (Cock of Strasbourg clock).*

Thus the many details of his clock can hardly be treated as an integral part of the history of technology. It is, however, worthy of mention that there was a dial for each planet, and that the trains for those of the Moon and Mercury embodied oval cog-wheels (figure 388). The two oval cog-wheels in the train of the Moon were divided into unequal sectors, each with the same number of teeth. The inner cog-wheel was fixed to the hub of a wheel with regular circular motion and thus provided for a regular increase in the Moon's phase in equal periods of time. The outer oval cog-wheel was carried around the inner, and by reason of the equal number of teeth in the unequal sectors provided for the varying length of arc traversed in successive equal time-intervals.

Almost contemporary with Dondi's great work is the Strasbourg clock of 1354. Its much simpler construction was widely imitated in succeeding centuries.

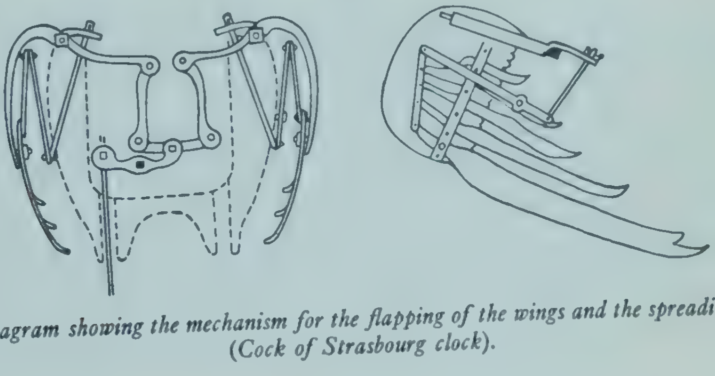

FIGURE 391—*Diagram showing the mechanism for the flapping of the wings and the spreading of the feathers (Cock of Strasbourg clock).*

This clock introduced another feature, namely automata or moving images. Of these the wrought iron cock, recalling St Peter's denial of his Master, is a unique survival. The clock was about 38 ft high and had an annual calendar wheel about 9 ft in diameter. At noon the cock opened its beak, stretched out its tongue, crowed, flapped its wings, and spread its feathers. The crowing was worked mechanically by bellows and a reed. This cock was used again in 1574 by Isaac Habrecht in making a second clock, hence no doubt its survival (figures 389–91).

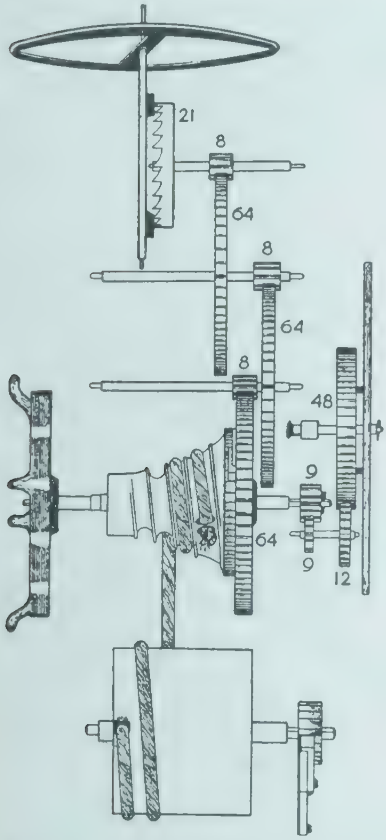

FIGURE 392—*Reconstruction of a clock with fusee from a manuscript of 1477. The number of fusees shown in the manuscript indicates that they were already well known at the time.*

III. THE SPRING-DRIVE AND ITS REGULATION

In a weight-driven clock the motive force remains sensibly constant, but the clock has to be permanently fixed. To make clocks portable the idea was conceived of replacing the weight by a coiled spring. This invention appeared in the fifteenth century or perhaps even earlier.

The earliest timepieces or watches carried on the person were usually drum-shaped. They have been miscalled 'Nuremberg eggs'[1] as they were believed to have originated in that city. This is now in doubt. A letter of 1488 from Milan refers to three watches of which two will strike but not the third [3]. Probably they were small portable clocks or watches carried on the person.

The earliest representation of a spring-driven clock is in a portrait of the middle years of the fifteenth century (plate 32 B). Its shape is in general that of the contemporary weight-driven type; it has, however, a notably thick base which probably contained spring-barrels connected by gut-lines to the drums on the great wheel-arbors, seen on the right in the striking-train. Attached to the arbor of each drum is a disk with four thumb-pieces for winding: the winding-key was a later invention. Both the inscription across the top of the canvas and the suspension of the clock suggest that it was carried from room to room.

The *fusee*, essentially a mechanism for equalizing the force transmitted to the gear-train, was rendered necessary by the diminishing force of the uncoiling spring. The invention, which is still in use, is first illustrated and described by Paulus Alemannus in a manuscript written in Rome in 1477 (figure 392). This shows a spring-driven clock fitted with a fusee through which passes a rigidly fixed arbor. At the end of this arbor is a disk with thumb winding-pieces (plate 32 B). The Latin text uses the words *corda* (gut) and *fusella* (fusee) and relates that the great wheel carrying the fusee made one revolution in three hours. Given a half-second oscillation of the balance-wheel at the top, that is, with one tooth of the crown-wheel escaping each second and with the number of the teeth of the wheels and pinions given by the text, in three hours the clock would indicate 10 752 seconds, only 48 seconds short of the three-hourly period. A similar mechanism is to be seen in well known sketches of Leonardo da Vinci, of perhaps 1490 (figure 393).

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[1] By translating 'little eggs' (= *Eierlein*) in mistake for 'little clock' (= *Uhrlein*).

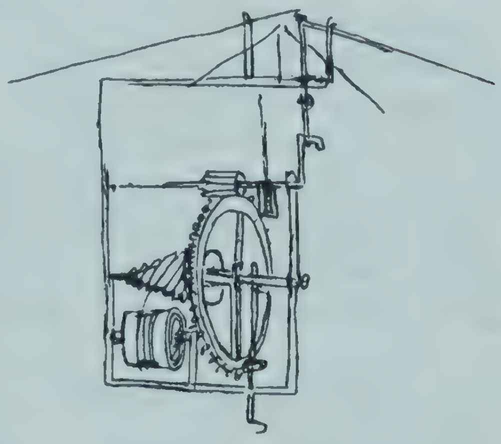


FIGURE 393—*One of Leonardo's drawings of the fusee.*

Another method of securing a constant drive despite the continuous weakening of the spring's tension was the *stackfreed* (figure 394). This is a kidney-shaped cam fixed to a wheel and having a stop-piece. The wheel is driven by a pinion fixed squarely to the arbor of the mainspring. Against the cam bears the head of a stiff spring, the pressure from which on the edge of the cam diminishes as the wheel turns during the uncoiling of the spring. The stackfreed also limited the effective number of turns in the spring to those giving the most even results.

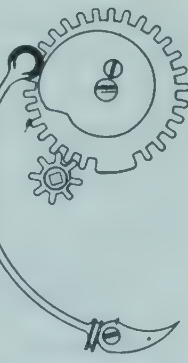


FIGURE 394—*The stackfreed—the term is of unknown origin. With 8 leaves on the pinion and 27 teeth on the wheel only just over the first three turns of the spring—those giving the most equal force—would be effective before the watch stopped and had to be rewound.*

Screws are important for the construction of clocks, but the date of their first use in this connexion is uncertain. Leonardo shows the tapping of female screw-threads in metal, and it is generally accepted that screws were adopted in clock-construction about the end of the fifteenth century. At this time, too, hog's bristles began to be used as a fine means of regulation. They served as *banking-pins* limiting the amplitude of the oscillations of the balance (figure 395). They reduced the strain imposed on the train by the reversal of the swing of the balance and so permitted the use of smaller driving-forces. They also damped banking, the factor in the dissipation of energy most difficult to control; so this new device greatly increased accuracy. On the other hand, it introduced certain errors, such as difference in resilience between bristles, or the incidence of impact through variation of control when a pallet was not in engagement. Thus bristle-regulation could give highly accurate results for a while, but these were liable to deteriorate.

After the introduction of the quarters strike, it became not unusual to introduce a small dial marked 1–4, indicating the quarters, as well as the hour-dial; later the figures 15, 30, 45, and 60 were added, and soon we find the minutes marked. They were first indicated without the use of a separate minute-hand. The concentric minute-hand did not come into general use until after the invention of the pendulum.

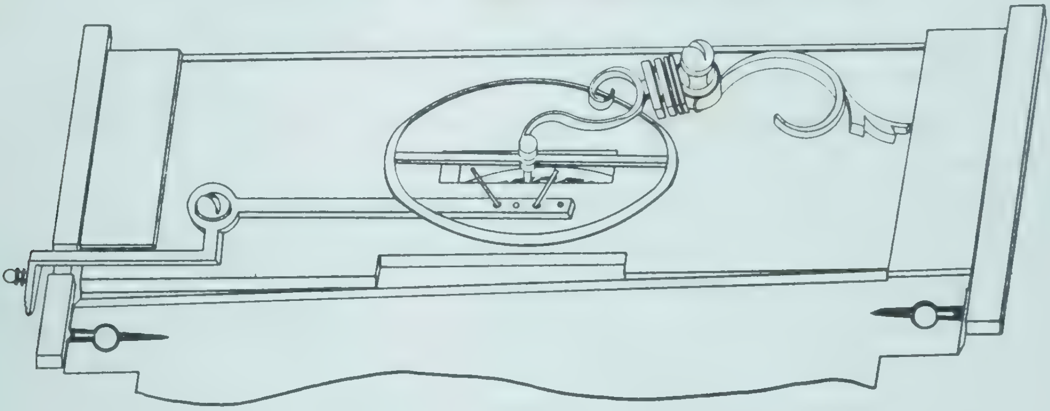
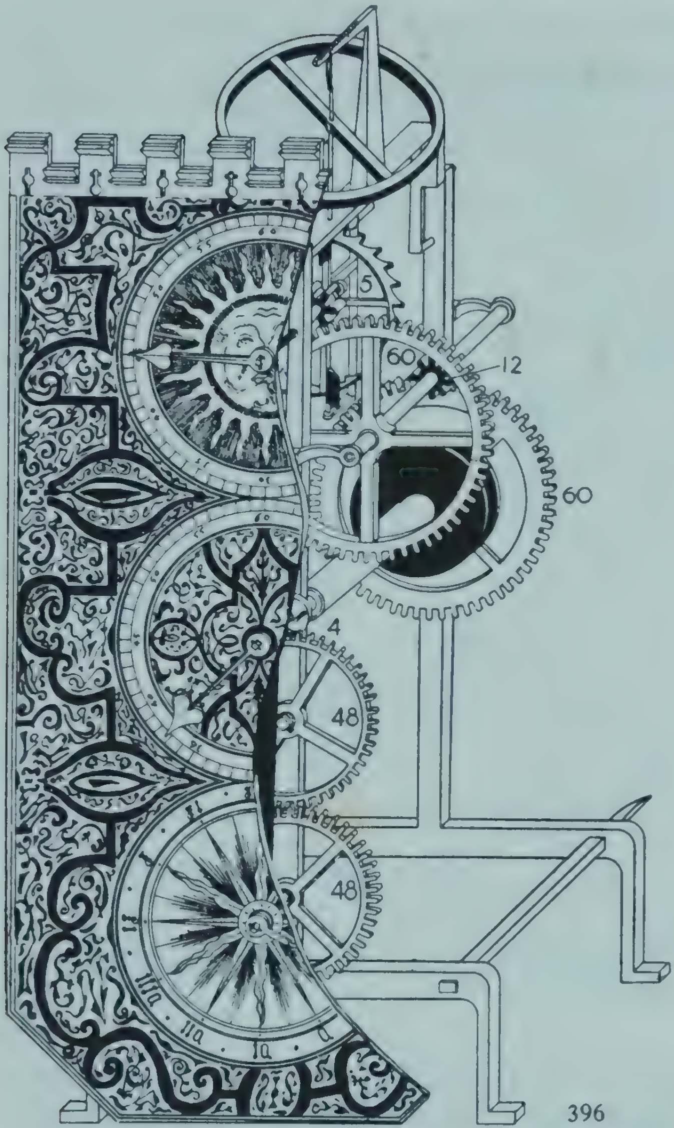


FIGURE 395—*Hog's-bristle regulation. Note the alternative holes and the cranked lever for adjustment.*

Tentative efforts were made to indicate seconds about 1550 (figure 396), but the seconds-hand was not regularly employed until after 1670, when William Clement introduced his anchor-escapement (p 665). This made the pendulum with a period of one second fully practicable for domestic clocks.

In 1561 Eberhardt Baldewin, clockmaker to William IV of Hesse, constructed an astronomical clock worthy of consideration as a successor to Dondi's (p 653). It was of great complexity. New features are an endless worm as a means of transmission, roller bearings, and cardan joints (figures 397, 398). This clock was made within about twenty years of Cardan's 'invention' of the universal joint.

At the end of the sixteenth century, astronomers—notably Tycho Brahe (1546–1601) and Kepler (1571–1630)—were well aware of the inadequacy of existing clocks, which were ineffective for astronomical purposes. The Swiss Jobst Burgi (1552–1632), a very skilled instrument-maker, applied himself at Cassel and later at Prague to meet their needs. His first care was to provide a



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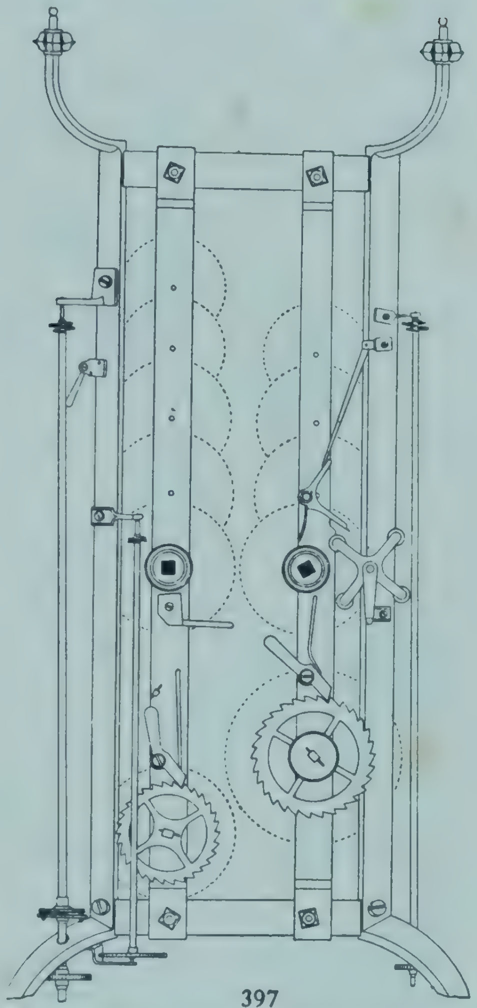

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FIGURE 396—*A little clock dating from c 1550, about 9 in high. It has three dials, showing seconds, minutes, and hours; it would be regulated entirely by varying the weight. The crown-wheels of verge-escapements have an odd number of teeth, so that seconds cannot be recorded exactly.*

FIGURE 397—*Baldewin's clock. Parts of the astronomical trains are fixed behind their respective dials fitted to each of the four sides of the inner frame depicted. The motions are transmitted from the going-train through a series of 24-hour wheels housed below the main trains* (these are not shown). *These wheels rotate others at the base of the connecting-rods, which are geared to the astronomical trains by endless screws. The eight dials are at two levels on each of the four faces. To enable the distant ends of the connecting-rods to mesh with their associated wheels, many of which are out of line, cardan joints are employed, one of which is illustrated.*

constant driving-force with a long period of action. A weight provided the former but needed frequent rewinding, with a consequent loss of accuracy, since maintaining-power[1] was yet unknown. Further, Tycho complained that the weight of the uncoiled rope caused an error of as many as four seconds in a few hours [4]. A spring could give a long going-period, but it was difficult to render its force uniform. Burgi therefore combined a driving-weight with a spring to restore the weight automatically every twenty-four hours (figure 399).

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[1] A device for maintaining the force on the train while the main weight or spring is rewound.

In this clock Burgi used the balance with bristle-regulation and the ordinary verge-escapement (figure 395). The limitations of the verge led him to design his *cross-beat escapement* (figure 400). In this the pallets are carried by separate arms geared together, allowing a much more delicate adjustment of the angle between their faces, according to the fineness of the teeth on the gearing. The shape of his escape-wheel teeth also allowed finer adjustment than did the ordinary verge. Its action is, in effect, the same as that of a bristle set to make contact with the balance at the moment of pallet-collision; but since the elastic properties of the metallic arm are more constant than those of the bristle, the period of reversal is shorter and independent of setting; the oscillations are thus more symmetrical. Finally, the flexibility of the arms of the cross-beat lessens the wear on the escape-wheel teeth and pallets. This escapement, although used for only a short period, made a real contribution to the exactness of the clock. With the introduction of the pendulum clock the cross-beat was superseded, and the mechanical time-keeper could be widely applied to astronomical observations.

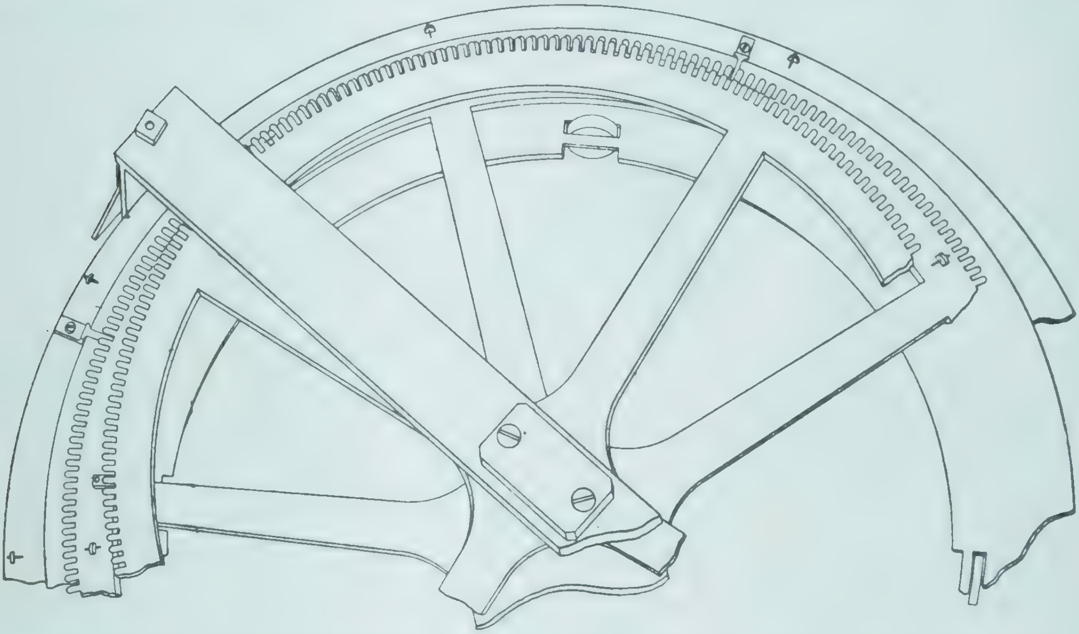

Figure 398—*Part of the train operating the dial of Mercury, showing Baldewin's use of roller-bearings as a means of support.*

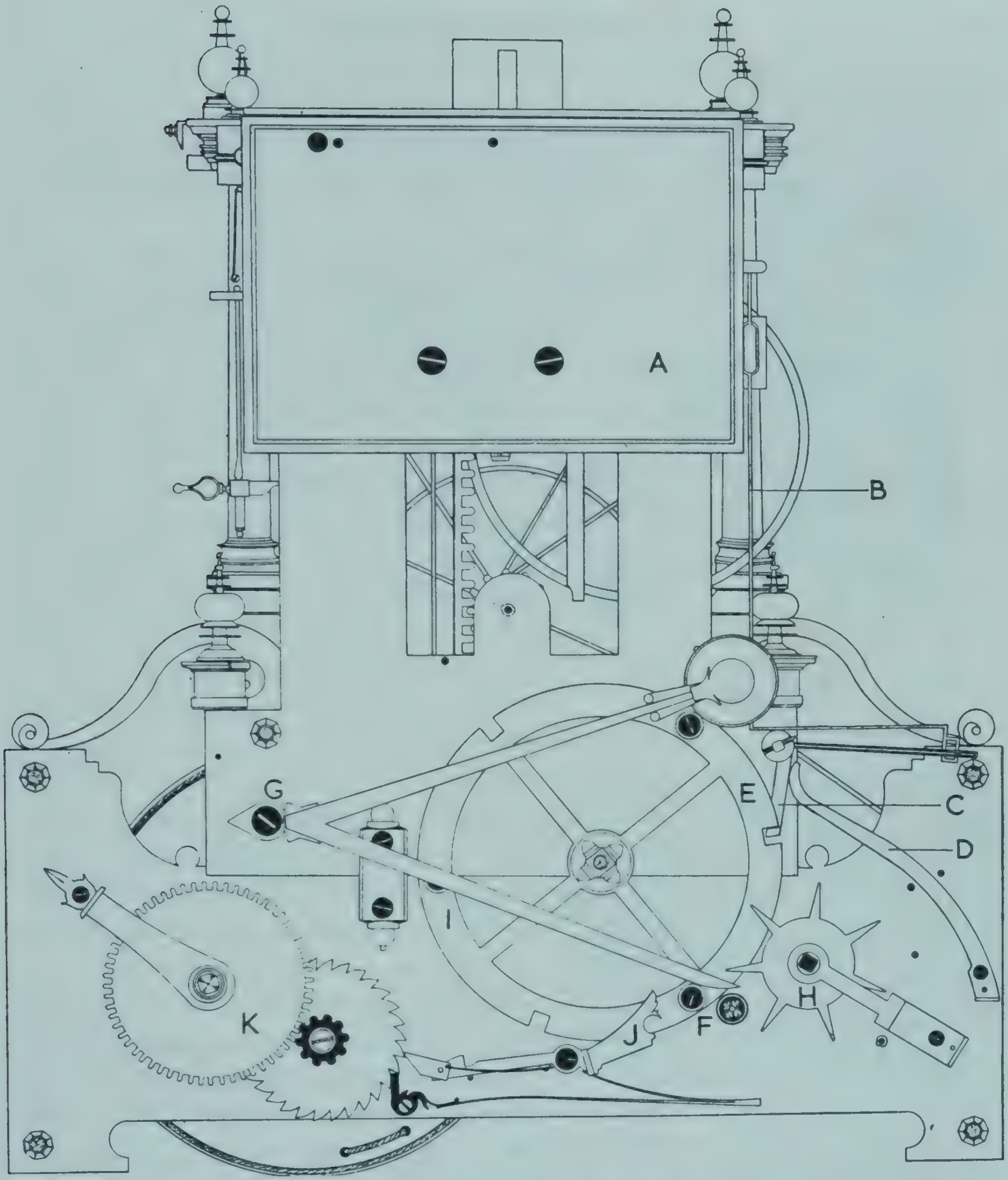

FIGURE 399—*Burgi's remontoire. The weight, a rectangular box* (A), *contains lead pellets, providing a means of fine adjustment. This constant driving-force during its 24-hour descent depresses the lever* (B) *which indirectly moves the catch* (C), *controlled by the spring* (D), *to the right, releasing the spring-driven locking-plate* (E). *This now turns anti-clockwise, carrying with it by means of the stud* (F) *the* V*-shaped arm pivoted at* (G). *The weight, now resting on the roller at the other end of the* V *arm, is restored to its higher position, the upper arm of the* V *being clear of the studs. The end of the lower arm slides off the stud* (F), *the* V *arm drops back into position, and* D *presses* C *into the next notch in the locking-plate. The lower arm of the* V *in passing knocks the 7-star wheel* (H) *carrying the day of the week dial one tooth forward. The stud* (I) *depresses the pawl* (J) *and through the ratchet-wheel and pinion moves the wheel* (K), *which carries the dial recording the number of times the remontoire has functioned one tooth forward. The spring will operate for three months and the remontoire counter can record 180 actions. This is the earliest remontoire known.*

IV. THE PENDULUM

The association of the pendulum with time-keeping is linked primarily with the names of Galileo (1564–1642) and Huygens (1629–95). It introduces a new era in horology.

Galileo is said to have conceived the new principle of isochronism in 1581 when watching the swinging of the lamps in the cathedral at Pisa. He timed their oscillations by his pulse, and then ascertained experimentally that the period of oscillation for any given length of pendulum was constant and independent of amplitude. This is approximately correct. He does not seem to have related this idea clearly to clock-work until about 1641. Being then blind, he gave instructions to his son, Vincenzio, for combining his pendulum and escapement in a clock (figure 401). Vincenzio delayed its construction until 1649 and himself died before its completion. Meanwhile the isochronous pendulum maintained by hand had been used by astronomers.

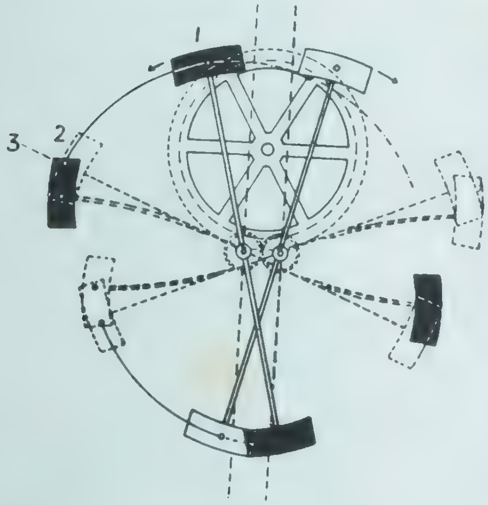

FIGURE 400—*Burgi's cross-beat escapement in diagrammatic form. The dotted vertical lines indicate the mean position of the arms about to cross.* Position 1: *the pallet on the shaded arm engages with the tooth of the escape-wheel, while swinging in the direction of the arrow.* Position 2: *the pallet is liberated and the arms swing freely until at* Position 3 *the pallet of the other arm engages and causes a check. Because of the flexibility of the arms, there is no jarring impact. The restoration of the flexed arm to its normal shape provides an impulse for the return in the opposite direction. In the figure this flexure has been exaggerated for clarity.*

Galileo's escapement was of the pin-wheel type, which did not come into extensive use until over a century later. His pendulum had an amplitude of only about five or six degrees, thus largely eliminating circular error, though he did not realize that this error existed. Another model, in which a very slight modification had been made, was in modern times fitted to a weight-driven clock-train, and showed variations of no more than a few seconds a day. The seafaring Dutch were deeply interested in determining longitude at sea and in this connexion Galileo had approached the States General suggesting the adoption of a pendulum with a recording-device (actually impracticable) for counting the oscillations. Huygens must have been aware of this suggestion but knew nothing of Galileo's escapement.

Huygens's own pendulum-escapement incorporated the much inferior verge mechanism. He started his experiments in 1656 and published the first work on the pendulum clock, *Horologium*,[1] in 1658. It is clear that he then knew that amplitude affects isochronism (figure 402). No clock constructed on these lines has survived. Before introducing his arrangement of pinion and contrate wheel, Huygens had several clocks made with pendulums swinging in an unrestricted arc. Later he reverted to the horizontal crown-wheel and pallets, while controlling the arc of oscillation by curved cheeks, fitted at the point of suspension of the pendulum. The curves of the first cheeks fitted to clocks by Huygens were arcs of circles. The clock claimed to be the first made by Salomon da Coster, Huygens's clock-maker in the Hague, which is now in the Museum for the History of Science at Leiden,[2] has a horizontal crown-wheel and is spring-driven. Coster made many pendulum clocks to Huygens's design and these were the first to be commercially available.

Huygens discovered the importance of the cycloid[3] for horology in 1659 and published his investigations in his second and greater work on time-pieces, the *Horologium oscillatorium* (Paris, 1673) (figure 403). In this he described the theory leading him to the view that the truly isochronous pendulum must swing in a cycloidal arc, which is slightly narrower than the corresponding arc of a circle. In practice the cycloidal cheeks he introduced to this end, though of the greatest theoretical interest and much used by him, introduced more errors than they corrected. Huygens's pendulum was brought to London by the clock-making family of Fromanteel, which was of Dutch origin. One of them learnt the secret of the pendulum from da Coster. The cycloidal cheek was, however, never widely adopted in England, where

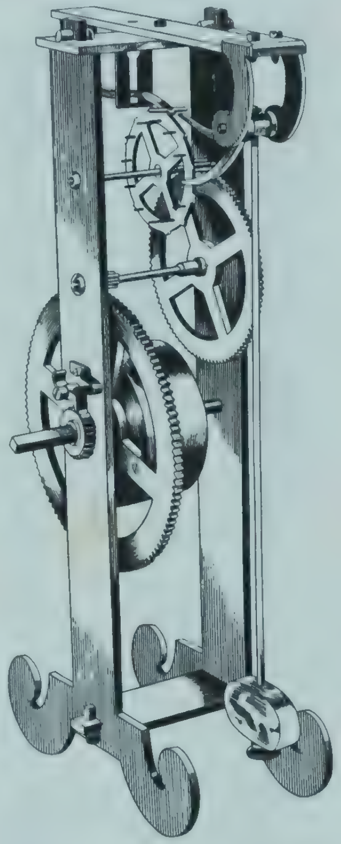

FIGURE 401—*Galileo's pendulum escapement. The escape-wheel, bearing on one side twelve pins projecting at right-angles, has twelve small bosses or teeth which are locked by a hinged detent. As the pendulum swings to the left, the unlocking pallet raises the detent and the wheel revolves until a pin strikes the impulse pallet. As the pendulum swings to the right the impulse pallet is freed from the pin; at the same time the locking pallet releases the detent, which then falls upon the rim of the wheel to lock it.*

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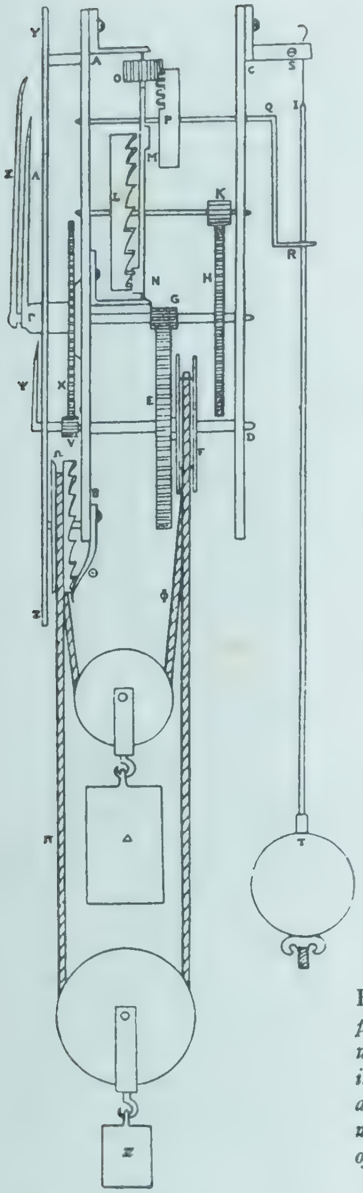
[1] Not to be confused with his *Horologium oscillatorium* of 1673.

[2] The accuracy of this attribution is doubtful. See Drummond Robertson, 'The Evolution of Clockwork', pp 76–78.

[3] A cycloid is a curve traced by a point on a circle as the circle rolls along a straight line. The end of a string wrapped round a cycloid describes a second cycloid (the evolute); this was the property of the curve exploited by Hugyens in designing his 'cheeks'.



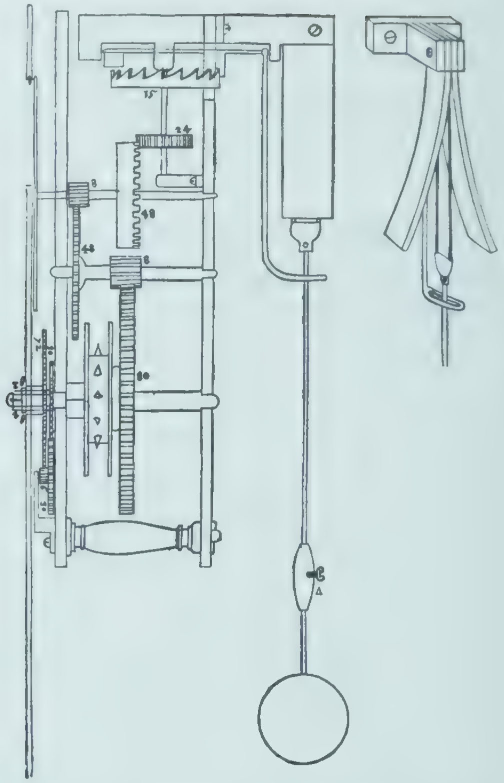


FIGURE 403—*Huygens's clock with cycloidal cheeks. The crown-wheel is horizontal, eliminating the pinion and contrate wheel of figure 402. The pendulum crutch is attached directly to the verge-pallet arbor. Maintaining-power is not shown, but could easily be fitted.*

FIGURE 402—*Huygens's first pendulum clock: the amplitude of the half-seconds pendulum with verge-escapement is reduced by a pinion engaging with a contrate wheel of three times its diameter, fixed to the crutch arbor. Maintaining-power is introduced for the first time. A saw-toothed wheel is fixed to a pulley Ω. A detent Θ allows movement only in the direction raising the weight. A secondary weight Z ensures that the endless rope is taut. In this arrangement half the weight of Δ is always effective in the cord Φ and it will always maintain motion in the time-piece while the weight is drawn upwards by pulling the cord Π.*

it was usual to attach the pendulum rod directly to the verge-pallet arbor. Later the practice was to suspend the pendulum independently and actuate it through a crutch, as originally done by Huygens, but employing a flat spring for the suspension in place of a silk cord.

V. THE ANCHOR-ESCAPEMENT

The anchor-escapement of William Clement (figure 404), invented about 1670, rapidly displaced the verge-escapement in England, except for mantel clocks which were then carried from room to room, since the verge-escapement needs less exact levelling. After the death of Huygens the anchor-escapement was soon generally adopted on the European continent.

In the anchor-escapement the faces of the pallets of the escapement are in the same plane as those of the teeth of the escape-wheel, enabling them to effect clearance within a much smaller arc than was necessary for the verge-escapement. This was of great advantage, because the isochronism of a pendulum is affected by its amplitude; the smaller the arc of circle described, the more closely it approximates to a cycloidal arc. Theoretically these two curves coincide only at the mid-point of a pendulum's swing, but in practice they are indistinguishable mechanically if the swings are of small amplitude on either side of this point: hence the smaller the swing of the pendulum the more nearly it is isochronous (figure 405). Another advantage of the anchor-escapement was that it freed the pendulum from its contact with the escape-wheel to a limited extent, as against the uninterrupted contact of the verge, and so made the first step towards that unattainable ideal, a clock with a perfectly free pendulum. It had, however, the disadvantage that the pallet strikes the face of the escape-wheel tooth, causing a recoil. The effect of this may be seen in an ordinary long-case clock as a slight shudder in the seconds-hand each second.

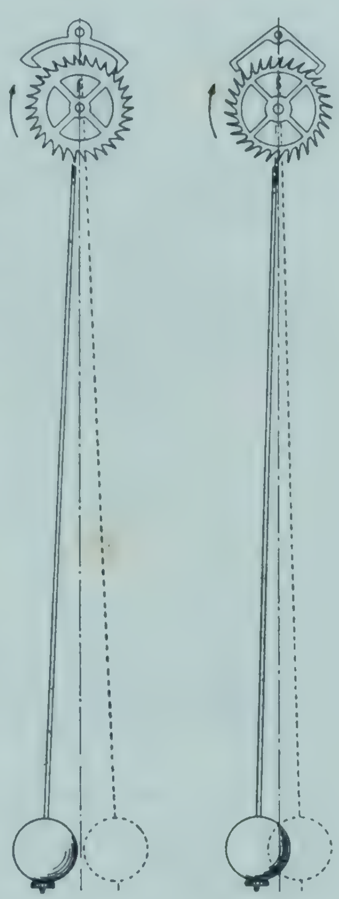


FIGURE 404—(Left) *William Clement's anchor-escapement. Note the small amplitude of the pendulum and the way in which the pallet strikes the face of the tooth of the escape-wheel, causing recoil. Compare* (right) *Graham's deadbeat escapement in which the recoil is avoided. The amplitude of the pendulum's swing is here still less.*

Despite its inherent imperfections the anchor-escapement was a great advance. Because of its small amplitude it enabled the 39-in seconds-pendulum to be adopted generally for both domestic and scientific use, the long-case clock, as we know it today, immediately becoming popular. In scientific circles the vastly improved timekeeping of the anchor-escapement, with the long seconds-pendulum, was quickly recognized. In an attempt to secure still higher accuracy clocks were made with 5-ft pendulums, beating 1·25 seconds, while Thomas Tompion went yet further and built in 1676, for use in the newly established observatory at Greenwich, two clocks with 13-ft pendulums, beating 2 seconds,

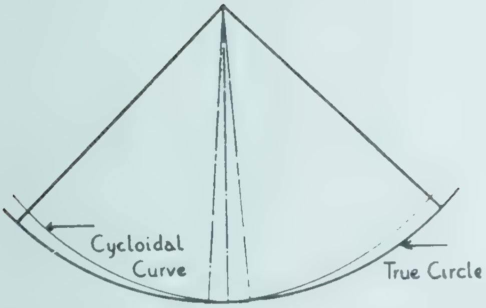


Figure 405—*Diagram illustrating the coincidence of the circle and the cycloid over a very limited arc, and indicating the significance of the anchor-escapement, figure 404.*

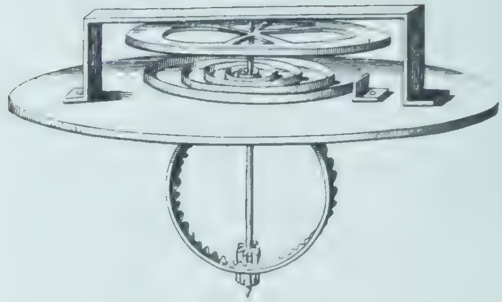


Figure 406—*Huygens's balance-spring was a spiral of many turns; acting through a pinion and contrate wheel, it made several revolutions at each beat.*

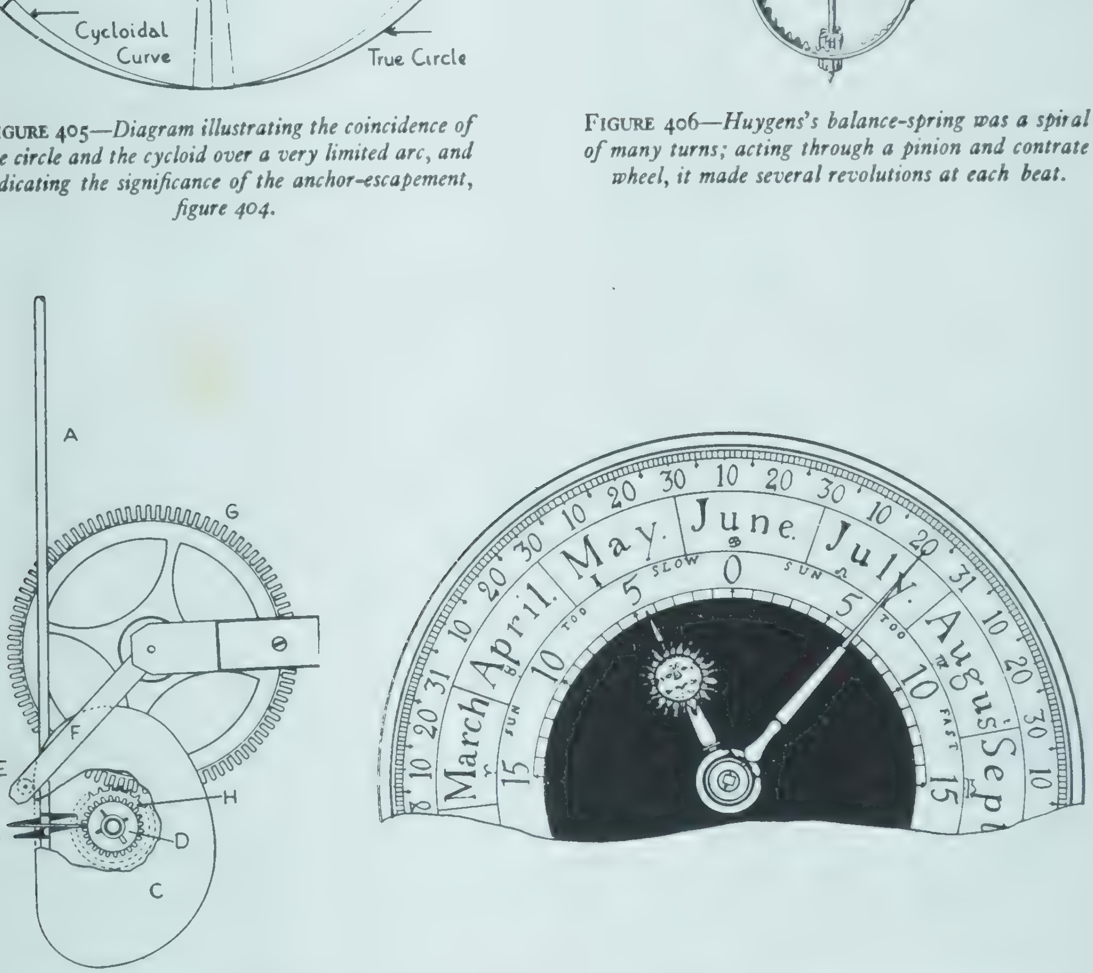


Figure 407—*Equation movement.* A *is a rod rotated by the clock-train which through the worm* (B) *and wheel* (D) *turns the equation-kidney* (C) *once a year. As* C *turns, the pin* (E) *on the arm* (F) *approaches or recedes from its centre, giving a forward or backward motion to the wheel* (G), *which in turn transmits it to wheel* H. *This is attached to a friction-tight sleeve arbor carrying the equation-hand with the effigy of the sun. Fixed to the arbor of* C, *and thus turning once a year, is the annual calendar hand. In wheel* G *only the lower teeth are shaped, since this sector of the wheel alone is used. The remaining teeth are cut for balance. Sometimes a counterpoised toothed rack is used. When the equation-movement is integral with the clock-movement, the equation is shown either by a second, mobile, minute-ring or, later, by fixing the equation-hand as a sleeve-fit on the arbor of the minute-hand of the clock.*

fitted with maintaining-power, and going for one year with one winding. Except for their maintaining-power these were probably the first clocks to be made incorporating these innovations. They were not an entire success but were a great deal better than those then available in other observatories. They were largely responsible for the accuracy of the stellar tables compiled by Flamsteed (1646–1719), the first Astronomer Royal.

At the other end of the scale we have the astronomer James Gregory, who in 1673 was at St Andrews University, ordering from Joseph Knibb of London two long-case clocks with seconds-pendulums and a small clock with anchor-escapement, having 90 teeth in the escape-wheel and beating one-third of a second. This last had only two hands, one for the hour and the other to record thirds of a second.[1] It was the first clock designed to record a split second and so was the first step on the road towards the fractional-second measurements of today: all due to the anchor-escapement.

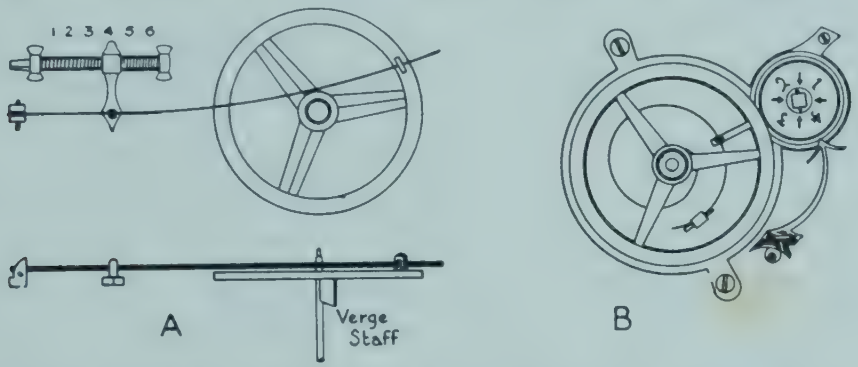


FIGURE 408—*Early forms of balance-spring.* (A) *A straight spring acting on the rim of the balance was used in some early experiments. The figure also illustrates the 'Barrow' screw regulator.* (B) *Early balance-springs usually consisted of $1\frac{1}{2}$ turns only. This drawing shows Tompion's regulator in which a curved sector, corresponding to the outer curve of the spring, and carrying the arm with the curb pins, is controlled by a toothed wheel.*

The higher degree of time-keeping now achieved brought to the notice of the general public the difference between the mean and the solar day throughout the year, known as the equation of time. The difference arises from two facts, (*a*) the inclination of the Earth's axis to the plane of its orbit, and (*b*) the greater velocity of the Earth's revolution in its orbit at perihelion (in winter) than at aphelion (in summer). Only on four days of the year is the solar day of exactly 24 mean hours; the maximum variations of the solar day from the mean day are such that the Sun is 14 minutes behind mean time in February and 16 minutes in advance of the clock in November. The days of equality are irregularly spaced,

[1] These three clocks are still in the library of St Andrews University.

and the daily variation, sometimes fast and sometimes slow on the mean clock, is also irregular. At first, tables were printed and were stuck inside the door of a long-case clock, showing how much a clock going correctly should be fast or slow by the sun-dial on any given day; later, manually operated adjustable dials were sometimes made, until finally the problem of the mechanical recording of the equation was solved—it is believed by Christiaan Huygens, who designed a kidney-shaped cam (figure 407). These mechanical equation-clocks were first made about 1695.

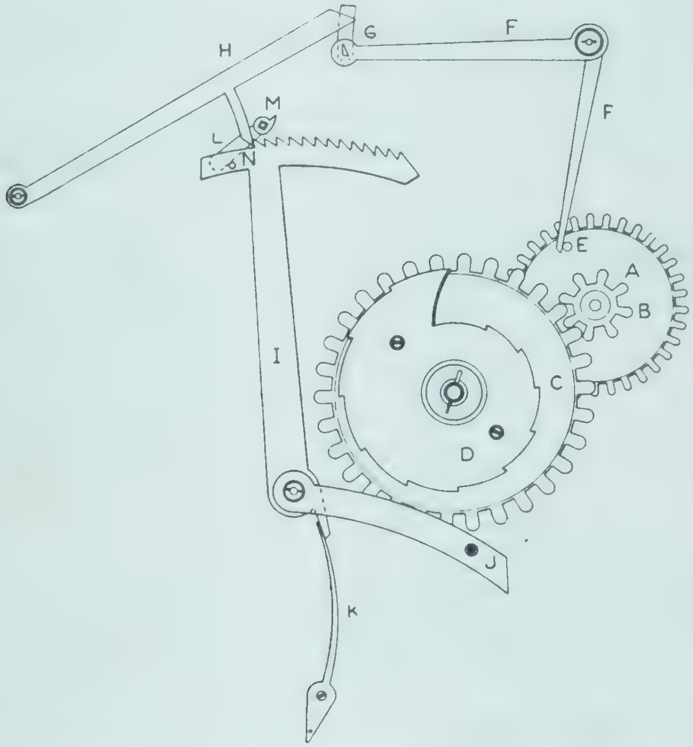


FIGURE 409—*Edward Barlow's rack-and-snail strike (diagrammatic). The minute wheel* (A) *turning once an hour through the pinion* (B) *drives the hour wheel* (C) *carrying the snail* (D) *into which are cut 12 progressively deeper steps. Once an hour the pin* (E) *lifts the detent* (F) *and through a pin on the far side* (G), *projecting through the front plate, releases the 'warning' wheel. At the same time the rack detent* (H) *is raised, allowing the rack* (I) *to fall to the left (under the action of the spring* (K)) *until stopped by the pin* (J) *on its far side coming into contact with the edge of the snail* (D). *The number of teeth in the rack* (I) *passing the arm of the detent* (H) *is determined by the depth of the indenture on the snail. When* E *clears* F *the latter falls back, releasing the striking-train, and the arm of* H *will drop into the correct notch in the rack. The gathering pallet* (L) *on the arbor of the wheel operating the hammer will turn about on its pivot* (M), *gathering a tooth at each revolution, the teeth sliding under the arm of* H, *until the rack is moved back to the right to the position shown. Then the tail of* M *is locked by the pin* (N) *and striking ceases. In this striking-mechanism the hour hand is usually only a fairly tight friction-fit on its sleeve arbor, so that if the striking becomes incorrect the hand can be turned to the correct hour without damage.*

The greatly improved time-keeping of clocks brought about by the anchor-escapement inspired watch-makers to attempt to achieve equal accuracy in watches. In 1675 Huygens described his balance-spring, claiming that it would render a watch sufficiently accurate to enable the longitude to be found at sea (figure 406). Hooke claimed priority, and whatever may be the truth of that, it was certainly Hooke's balance-spring, oscillating through about 120°, as opposed to Huygens's, with its pirouette of several turns, that was generally adopted (figure 408).

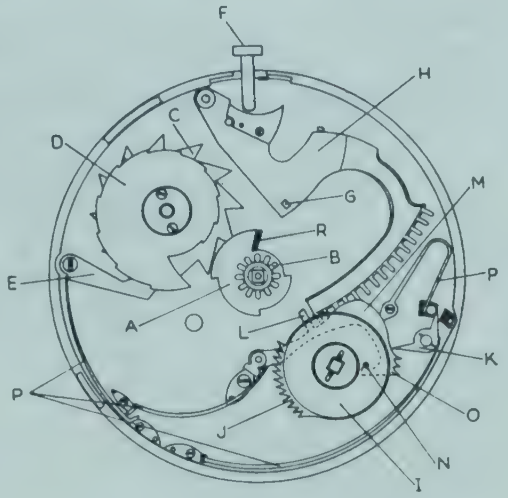


FIGURE 410—*Early repeating-work by Daniel Quare.* A *is the quarter snail which is turned once an hour by the wheel* (B) *to which it is secured. On its underside it has a pin which knocks the 12-pointed star-wheel* (C), *fixed beneath the hour snail* (D), *forward one tooth each hour.* C *is steadied by a detent* (E). *When the plunger* (F) *is pushed in, the stud* (G) *on the arm* (H) *falls upon the hour snail in the correct position. The rack end of* H *advances by the number of teeth corresponding to the step in the snail and winds the spring, enclosed in the barrel* (I), *the requisite amount. It also causes the hour-rack* (J) *to turn anti-clockwise, placing the correct number of its teeth in position for actuating the pallet* (K). *As* I *turns anti-clockwise the movement of the pin* (N) *allows the quarter-rack* (M) *to advance until its arm* (L) *reaches a step on the quarter snail* (A). *When* H *returns to its original position* I *turns clockwise, striking the hours by means of* J *and* K*; shortly afterwards* N *impinges on* M *and restores it to its original position, so striking the quarters through* O *and* K. *The pallet* (K) *is on the arbor of the wheel* (not shown) *controlling the hammer.* P, P, P, P *are restoring springs. Shown hatched on* A *is the 'surprise piece'* (R) *which operates when the repeat is to function within a few minutes either side of the hour.* R *is pivoted to* A *and is held in position by a spring* (not shown)*; it carries the pin that actuates the star-wheel. As this pin presses on the star-wheel,* R *is pushed back level with the edge of the quarter snail* (A), *returning to its former position when the pin has cleared the tooth of the wheel. This brings the hour and nil quarter into action at the same moment. In this early model the quarter is sounded with one stroke only; later a double stroke, 'ting-tang', was introduced.*

Watches with balance-springs were sometimes termed at this time 'pendulum-watches', because their accuracy was supposed to rival that of pendulum clocks. Sometimes the spring-regulated balance of an early watch takes the form of a dumb-bell bar, half of which is hidden by a solid cock, leaving the other half to give the impression of a swinging pendulum. Watches fitted with small pendulums were also occasionally made, the movement being mounted in gimbals, in the manner originally proposed by Huygens for a sea-going pendulum-chronometer.

A lesser advance was the invention by Edward Barlow, about 1676, of the *rack-and-snail* striking-method (figure 409). Since the snail revolves once in twelve hours, each step will take one hour to pass the stud on the end of the lever, so that if the clock be caused to repeat at any time during that hour the stud will fall on the same step of the snail, which will enable the gathering pallet to take in the same number of teeth each time and so correctly repeat the hour.

Repeating-clocks remained popular until the nineteenth century, when matches came into use.

There were many forms of repeating-mechanism. The simplest struck the hour only, then came the quarter-hour followed or preceded by the hour, usually on a higher-pitched bell; subsequently we find the half-quarter and finally the minute-repeater, of which the earliest known example is about 1705.

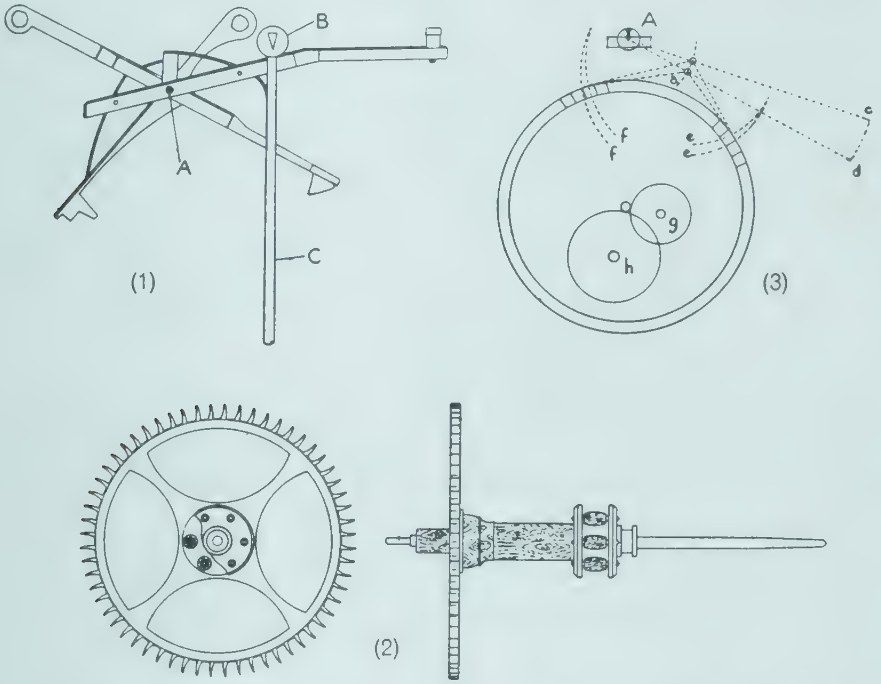


FIGURE 411—*The Harrisons' grasshopper escapement.* (1) *Shows the pallets, their centre of motion* (A) *offset from the pallet arbor* (B) *carrying the pendulum crutch* (C). *Note the knife-edge arbor finial which rested on a small piece of glass to reduce friction.* (2) *Shows the brass escape-wheel with its oak arbor and roller pinion of lignum vitae;* (3) *Harrison's own sketch of the layout of the escapement.* A *is a small glass plate with a groove supporting the knife-edge of the pallet arbor.* c–d *is the smallest arc of the pendulum clearing one tooth in the escape-wheel. The offset centre of motion of the pallets will move through the arc* a. *The extremities of the pallets describe the arcs* e–e *and* f–f, *the distance between these arcs at the circumference of the escape-wheel being half the distance between teeth. As the centre of their motion is mobile the friction between pallet and tooth is greatly reduced.* g *and* h *are rollers supporting the escape-wheel arbor to reduce friction.*

In 1688 Daniel Quare and Edward Barlow were contestants for a patent for repeating-watches. The patent was awarded to Quare because his watch repeated both hour and quarter at the pressing of one lever, whereas Barlow's watch required separate actions (figure 410).

Another invention having a great effect on time-keeping was the piercing of jewels with minute holes, serving as almost frictionless and unwearing pivot-holes. A patent for this use of jewels was granted to Nicholas Faccio de Duillier, the inventor, and Peter and Jacob Debaufe, the watch-makers, in 1704. Faccio (1664–1753) was a Swiss who had settled in London in 1687. The jewels commonly employed were rubies and sapphires, the latter being the easier to pierce. The art of jewelling watch-bearings was kept a close secret, and was not generally practised on the continent until 1798. Nowadays the jewels employed are made artificially.

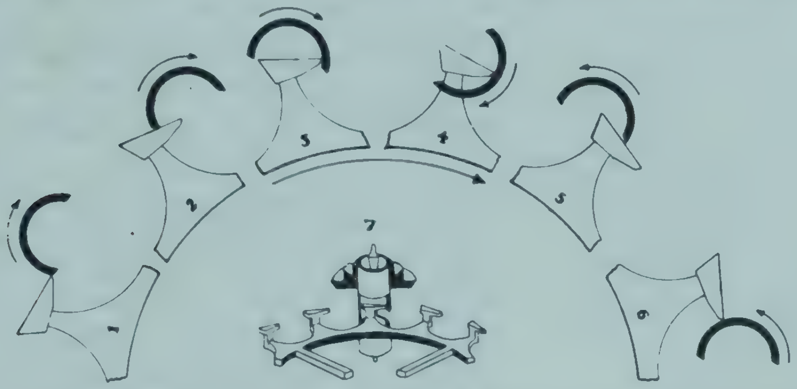


FIGURE 412—*Graham's cylinder-escapement.* (1) *A tooth is about to enter the cylinder.* (2) *Imparting the impulse by the sliding action along the cylinder lip.* (3) *The train is locked by the tooth's impinging on the cylinder wall.* (4) *The balance completes the swing due to the impulse at* (1). (5) *The balance-spring reverses direction and the balance receives an impulse as the tooth escapes.* (6) *Immediately the tooth escapes the next tooth impinges on the cylinder and locks the train during the period of backswing.* (7) *Section of the wheel and cylinder.*

VI. THE DEAD-BEAT ESCAPEMENT AND ITS SUCCESSORS

The great success of the anchor-escapement led astronomers to seek yet higher accuracy. George Graham, who was as famous both at home and abroad for his astronomical instruments as for his clocks and watches, applied himself to this problem and about 1715 invented a modification of the anchor-escapement known as Graham's dead-beat escapement (figure 404).[1] This found immediate favour, especially in observatories, where it was the standard escapement until Riefler's escapement was adopted after 1893, to be followed by the Shortt free-pendulum clock in the 1920s. This brings home the immense importance of the anchor-escapement which, in its sphere, is equal to that of the pendulum itself.

During the succeeding decade investigations were proceeding, both in this country and on the continent, into the comparative expansion of metals, for variations with temperature in the length of pendulums and of balance-springs seriously affected the accuracy of the finest clocks. George Graham made experiments with brass and iron, but abandoned them in favour of his mercury pendulum (*c* 1726). John and James Harrison were at the same time experimenting with iron–brass combinations and produced their gridiron pendulum.

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[1] A dead-beat escapement is one that operates without imposing any recoil on the train.

John Harrison (1693–1776) is best known for his struggle and final victory in the problem of making a time-piece sufficiently accurate to enable the longitude to be ascertained at sea, for which, over a period of years up to 1772, he was awarded the prize of £20 000 offered in 1714. John and his brother James were carpenters and sons of a carpenter; their first clocks were entirely of wood, except for the escape-wheel. Their main object was to reduce friction and to eliminate the use of oil. Disks of wood were used for the wheels; these were grooved and the teeth were inserted in groups of five. Oak was generally employed, but for pivot-bearings bushings of lignum vitae (*Guiacum*), a naturally oily wood, were inset. The arbor carrying the escape-pallets sometimes terminated in knife-edges which rocked on small plates of glass, as a bearing-surface, let into the wooden frame. To reduce friction further their pinions were built up of lignum vitae rollers revolving on small brass pins (figure 411).

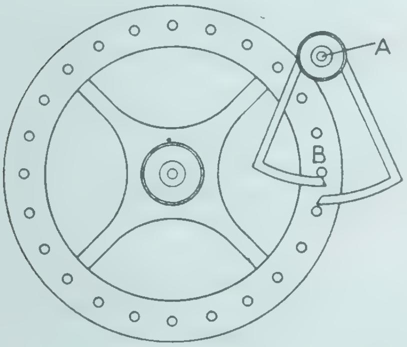
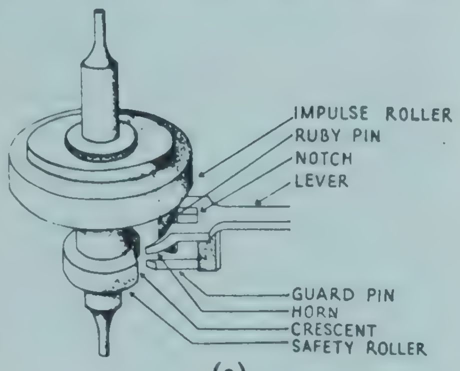


FIGURE 413—*Amant's pin-wheel escapement (p 674). The pallet arbor* (A) *is solid with the pendulum crutch. As the pendulum swings to the left the pin* (B) *on the escape-wheel will slide down the inclined face of the pallet, giving an impulse.* B *then drops upon the right-hand pallet, and when the pendulum has swung sufficiently far to the right, gives an impulse to the right-hand pallet in the opposite direction. This is a dead-beat escapement, mostly used in France.*

To avoid oiling the escape-pallets, with consequent deterioration in time-keeping as the oil thickened, James Harrison developed the *grasshopper escapement* (figure 411). This had a large circular motion and ensured that the pallet made a practically frictionless contact with the escape-wheel. Very delicate to make and difficult to adjust, this escapement was rarely employed except by the Harrisons; it had a wide arc of swing and had to be used in conjunction with cycloidal cheeks.

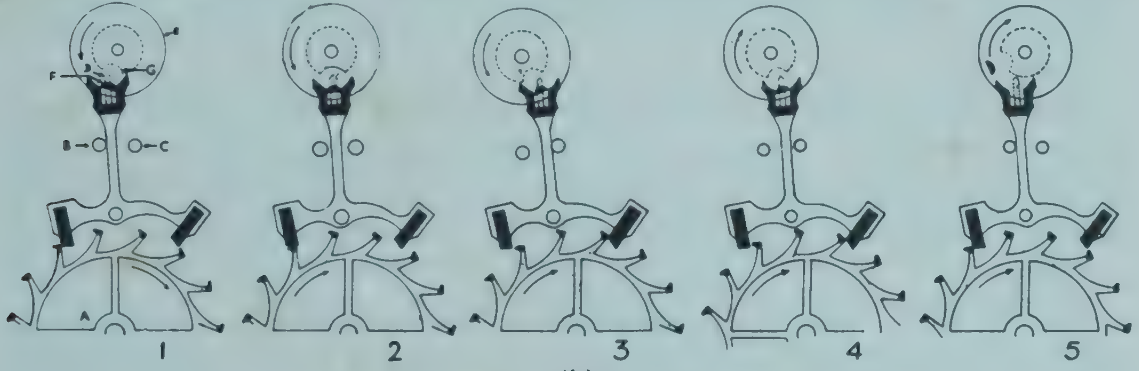
That the Harrisons' theories were sound and practical was proved very conclusively in 1955, when a turret clock made by James in 1727 was dismantled and examined. After the oil applied in ignorance had been removed it showed practically no signs of wear after 225 years. Yet Harrison's methods were very rarely imitated, and indeed, except for the bi-metallic temperature-compensation, John Harrison himself abandoned all his pet theories in the making of his 'Number Four', the chronometer with which he actually won the prize. Yet these ideas are so original and so effective that they deserve mention here.

After the advance in time-keeping in clocks resulting from the dead-beat escapement and pendulums with temperature-compensation, the next step was to improve the watch-escapement, which till then was the verge and balance-spring. George Graham invented the *cylinder-escapement* in 1721 (figure 412).[1] In this the escape-wheel is horizontal and in the same plane as the pallets. This allowed the watch to be more slender, but the chief advantage of the cylinder-escapement is that it is a dead-beat, and avoids the recoil inherent in the verge and the anchor. In the cylinder-escapement the escape-wheel remains locked by the cylinder during the supplementary arc of the balance, whereas in the verge it turns backward with it. The cylinder has, however, the same defect as the verge, in that the escape-wheel is never free and there is constant friction between the nose of the tooth and the inner wall of the cylinder. At that time



(a)

FIGURE 414—*Mudge's lever-escapement.* (a) *The staff carrying the balance and balance-spring shown in relation to the end of the lever. This should be studied in conjunction with* (b), *where* (1) *shows* A, *the escape-wheel, with its 'club-foot' teeth, and the lever with its jewelled pallets and fork or 'horns' at the other end.* B *and* C *are pins to limit lateral movement.* D *is the safety or guard pin.* E *is the impulse-roller, and* F *on the underside of* E *the impulse or ruby pin.* G *is the safety roller with crescent-shaped embrasure. The rectangular space between the horns is 'the notch'. The lever rests against* B, *the ruby pin is pressing the lever to the right.* (2) *The tooth, now unlocked, moves along the impulse-face of the pallet. The ruby pin, receiving an impulse from the notch at the same time, brings the lever against* C. (3) *The first tooth escapes and the next-but-one tooth to the right drops upon the locking-face of the exit pallet. The completion of the balance swing and its reversal until the next unlocking is detached; this free oscillation is the great advantage of the escapement.* (4) *The reversed swing of the balance causes the ruby pin to enter the notch from the other side, unlocking the exit pallet, which receives its impulse as the tooth passes over the pallet-face pressing the lever towards* B. (5) *The balance finishes its swing and on its reversal the ruby pin will again enter the notch as in* (1) *and the whole sequence will be repeated.*



(b)

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[1] Invented 1721; published 1726.

this was not a severe disadvantage, as the constant friction tended to equalize the irregularities introduced by the somewhat imperfect balance-springs of the day.

The cylinder-escapement was largely, but not wholly, employed by its inventor and was to a great extent the basis of his great reputation as a watch-maker. It was also fairly widely employed by a few of the better watch-makers in England and on the continent. In the main, however, the cheaper and simpler verge-escapement was standard until the general adoption of the lever escapement in the early nineteenth century.

There are many other escapements, but very few ever established themselves. One, of which a fair number was made for better-class watches, was the *duplex-escapement*, of which the inventor and date of invention are unknown. It was first systematically used by Pierre Leroy in Paris about 1750. This escapement requires a very high standard of workmanship; with that, it yields a very good performance, but as it is sensitive to variations in driving-force its use was confined to the more costly watches incorporating a fusee. The clearances are so fine that any wear on the pivots has an undue effect on the escapement; furthermore, as it is a single-beat escapement, it is liable to stop if subjected to a sudden jerk.

Another clock-escapement, sometimes employed in England but much more generally adopted in France, is the *pin-wheel*, invented about 1745 by the French maker Amant (figure 413). It was later improved by another French maker, Lepaute (1727–1802), who placed the pins alternately on each side of the wheel.

The last escapement to be mentioned is that found today in nearly every watch with any pretension to quality; it is the detached *lever-escapement* (figure 414). It was invented about 1755 by Thomas Mudge, but was not extensively used before the early nineteenth century. Mudge does not seem to have realized the importance of his idea, which was that in this design the escape-wheel is free from any connexion with the watch-train, except for the brief periods when the escape-wheel is locked and when it is receiving its impulse. There are many variants in the minor details of this escapement, but they all conform in its essentials. The form adopted by the Swiss manufacturers and now by the leading English firms, with its jewelled pallets and club-footed escape-wheel teeth, is that most widely used and is therefore the one illustrated.

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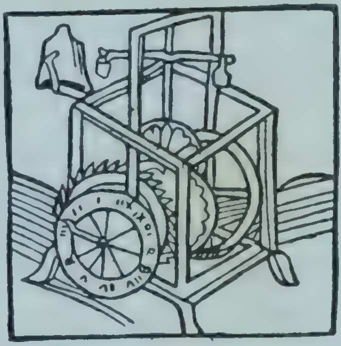

The earliest printed representation of a mechanical clock. c 1490.

25

INVENTION IN CHEMICAL INDUSTRIES

F. W. GIBBS

I. THE DEVELOPMENT OF CHEMICAL ARTS

THE German physician, Cornelius Agrippa of Nettesheim (1486–1535), told of a proverb current in his day that 'every alchemist is either a physician or a soap-maker'. From this we may gather that alchemists earned their livelihood not by making gold from the baser metals but rather by the practice of medicine or the chemical arts (plate 28). By itself, he inferred, the alchemical art would reduce the true chemist to a 'cacochimick' (charlatan), the physician to a 'fewterer' (greyhound-keeper), and the soap-boiler to the mean trade of meat-seller. On the other hand, he noted, there were many inventions that could be credited to alchemy in its more general sense, such as various colours, dyes, and pigments, latten metal (kinds of brass) and other alloys, methods of tinning and soldering, refining and assaying, the invention of the gun—'a fearful instrument', and the art of glass-making.

The introduction of printing with movable type about 1450 led to a vast increase in knowledge and a quickening of the imagination. The first printed books to treat of chemical invention consisted of gleanings from Pliny and other classical authors made by certain 'great and cunning Clearkes' of the Middle Ages, such as the great encyclopaedia of Bartholomew the Englishman (*c* 1250). These books continued in use throughout the sixteenth century, but the information they contained was largely that of centuries long past. There was little new in them. As Stillman said, the artisans of the Middle Ages were not writers of books; they were busy perfecting their chemical arts, sometimes indulging in alchemy on the side [1].

Until well into the seventeenth century there were two related movements in the chemical field that have a particular bearing on this subject: (*a*) attempts to rediscover old arts thought to have flourished in classical times and lost during the interval, and (*b*) attempts to produce new arts and improvements on the old.

The first of these showed itself in two main ways: first, the searching of classical writers and of manuscripts written by monks who were interested in such arts as limning, painting, dyeing, metal-working, and glass-making, and secondly, the travels through Europe, particularly Germany and Italy, of men qualified to inquire intelligently into, and to record at first hand, the techniques in use in various places. The searching of classical authors resulted in a book on lost arts, together with an account of new inventions not known to the ancients, by Guido Panciroli (1523–99), professor of civil law in Padua University [2]. Such books were a challenge to the age, and, when the work was translated into English in 1715, an account of the great discoveries that had been made since Panciroli's day—and particularly since the middle of the seventeenth century—was added to illustrate the fact that in recent years every science had found its Columbus.

One of the best examples of manuscripts on the arts was the treatise of Theophilus (vol II, p 351), copies of which were in circulation, especially in Germany and Italy, long before the age of printing. His work, for example, is referred to by Agrippa. The most famous book of the second type is the *De re metallica* (1556) of Georg Agricola (1494–1555) [3]. It is clear that much, sometimes all, of the information in books of both kinds was new only in the sense that it had not been available to a wide audience before. Thus most of the processes described by Agricola had been followed for some centuries, while writers making use of Theophilus were at times describing arts commonly practised in the Greek Byzantine period. Several countries and cultures had contributed to the information now being collected and distributed in the sixteenth century. Thus it has been said that Greece had been the painter, Tuscany the enameller, Arabia the worker in metals, Italy the jeweller, France the glassworker, and Spain the chemist, while Germany was anxious to acquire dexterity and knowledge in all these arts.

The second movement—the attempt to introduce new arts and to improve old ones—followed logically enough from the first. In general, however, men of different talents were required, inventors rather than chroniclers, men of 'art' rather than men of 'science'. These terms were in common use and signified something close to practice and theory respectively. When a chemist produced a thing 'by art', it was the result of his skill in chemical processes. Art was therefore not applied science, but a combination of techniques together with the special knowledge of materials gained in handling them. By art, attempts were made to bring about improvements in agriculture, which Samuel Hartlib (*c* 1599–*c* 1670) called the 'Mother of all other Trades and Scientificall Industries'. The art of metals, said Sir John Pettus (1613–90), was wholly chemistry. Some maintained that chemistry entered into all practical and 'mechanical' arts (as distinct from the liberal arts).

In the fifteenth century, owing largely to greatly increased demands for spirit of wine for other than medicinal purposes, the art of distillation had made rapid strides (pp 11–12, figures 7, 8). Improved methods were designed for the production of brandy, as also for that of the strong mineral acids needed by assayers and metallurgists (figure 40).

By the middle of the sixteenth century Germany led Europe in the practice of mining and metallurgy, and the Nuremberg area was pre-eminent in the manufacture of all types of metal goods. The great prowess of the Germans in these matters was attributed by Hartlib, in the middle of the seventeenth century, to 'their pertinacious industry in manual experiments, and . . . their great courage in daring to haunt untrodden paths in the quest of nature's secrets'.

The Republic of Venice, on the other hand, held pride of place in the manufacture of glass, especially on the island of Murano (plate 30). Processes were jealously guarded and the movements of workmen were often severely restricted. Thus in 1547 the Council of Ten at Venice had the power to execute any workman from Murano who went elsewhere to teach or practise the secrets of his trade. That Italy no longer enjoyed isolated leadership in the seventeenth century is shown by H. de Blancourt's *Art de la Verrerie* (1697), with its tribute to Colbert (1619–83), the great minister of Louis XIV, who was instrumental in bringing about a revival of French arts and manufactures; by the invention of cobalt blue (zaffre, smalt), soon to become a much-prized article of commerce, by the glass-blower Christoph Schürer of Saxony; and by the fact that flint-glass became known in Italy as *cristallo inglese*. (ch 9).

The fifteenth and sixteenth centuries also saw the rise of numerous majolica factories in central Italy, in which *piombo accordato*, a mixture of lead and tin oxidized together, was added to the alkali-silica mixture for the glaze. This technical secret enabled a large export trade to be developed, and more than thirty majolica factories were opened in Faenza alone between 1530 and 1550. Siena (Montalcino) had a reputation for such wares as well. Work on the production of new colours and enamels was also carried out. Success and secrecy often went together, however, and this sometimes led to the loss of important innovations, such as the new colours for ceramics introduced by the Andreolis of Gubbio (*c* 1500–40), the knowledge of which seems to have died with them. Some of the earliest European porcelain was made at Ferrara (see further in vol IV, ch 11).

The monopoly of the Italians in this field inspired men like Bernard Palissy (*c* 1510–89), the celebrated French potter, to emulate them. Through Palissy especially the ceramic industry outside Italy made considerable progress. His observations in this field, together with his appreciation of the value of chemistry and the experimental method, were given in his *L'Art de terre* [4]. The lasting value of his work is shown by the fact that during the nineteenth century Palissy-ware was imitated widely in England and at the imperial factory at Sèvres.

During the sixteenth century also, after new ocean routes to America and the East Indies had been opened up, there was an increased importation of numerous commodities previously unknown or obtained only in small quantities by overland routes. Many of these, particularly indigo and cochineal, had important applications in dyeing. Improved methods of fixing such colours on cloth were introduced—for example, the judicious use of a solution of pewter in *aqua fortis* for fixing cochineal as a scarlet dye. Italy achieved eminence in dyeing also, and the first textbook on the subject, *Plictho dell' arte de' tentori*, was produced by a Venetian, G. V. Rosetti, in 1540 [5].

II. SCIENCE AND INDUSTRY

During the age of Francis Bacon (1561–1626) the impact of science on the arts began to assume some importance. Bacon, who gave a practical bias to scientific learning, was doubtless influenced by the work of contemporary inventors in London, such as Sir Hugh Platt (1552–1611) and Cornelius Drebbel (1573–1633), the latter an arrival from Alkmaar in Holland.

Platt investigated the use of salt and marl in agriculture, produced fire-proof tubs, contrived fire-balls from small coal with loam as binder (p 80), introduced various new distillations, and made recommendations on chemical processes often carried out in the still-rooms of great houses with the aid of books of secrets such as the innumerable editions and recensions bearing the name of Alexis of Piedmont [6]. Platt also paid attention to the needs of navigators; for example, he made available an oily composition to prevent the rusting of iron-work, and his new kind of pitch was used by Sir Francis Drake on his later voyages. Platt looked into the question of keeping food and water wholesome at sea, and advocated the use of dried foods, such as Italian *pasta*, which would keep for long periods.

Drebbel's inventions were extremely varied and attracted attention throughout Europe. Among them were weapons devised for the Royal Navy, such as the floating petards used off La Rochelle in 1628, a more economical method for making spirit of sulphur, thermostatic controls for chemical furnaces and incubators (figure 415), and new processes for dyeing (p 695).

Bacon, holding that learning was too remote from everyday affairs, called for the collection of abstracts and 'patterns' of experiments from all sources and countries and their study by men skilled in discovering 'axioms' and 'aphorisms' for making further advances. Such studies, he thought, by those who combined practical skill to direct their use with mental perception to assess their value, would be of great advantage to mankind. The organization of this work demanded a society or college, where also the collections could be used for the preparation of a descriptive history of trades.

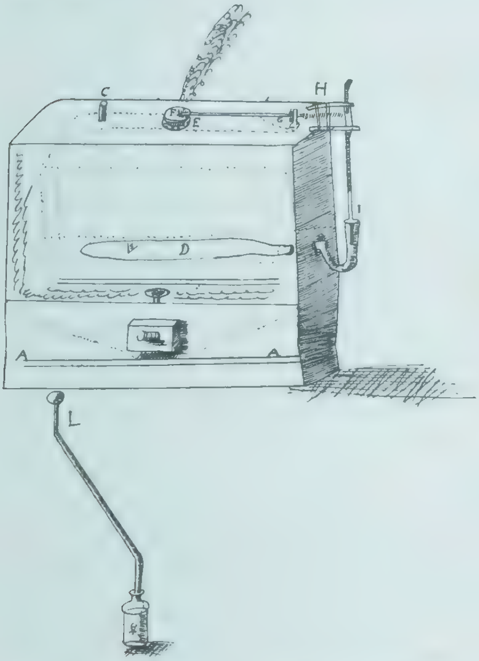

Figure 415—*Drebbel's automatic furnace or 'athanor' used as an incubator. The fire-grate* (A) *is at the bottom, the hot gases passing upwards round the inner box containing the eggs to emerge at* E. *This inner box is protected by a water-jacket in which is inserted a thermostat* (D) *filled with alcohol. Mercury fills the U-tube joined to it. As the alcohol expands, the mercury is forced upwards so raising the rod* (I), *which by means of the levers* (H) *closes the damper* (F). *If the heat falls too low, the action is reversed by contraction of the alcohol. The effect of the thermostat is adjusted by a screw at* H. *Another drawing shows a similar furnace without the water-jacket and with air in place of alcohol in the thermostat.* L *is an air-thermometer indicating the temperature of the furnace. From a manuscript of 1666. This furnace (not working) was seen by Monconys in 1663. It is perhaps the first example of a 'feed-back' mechanism.*

The 'Verulamian plan', as Bacon's proposals came to be known, stimulated many ideas but led to little immediate benefit. At his death, however, there were at least three young men in their twenties who thought on similar lines. Thus Edward Somerset (1601–67), second Marquis of Worcester, about 1628 employed a German gun-founder, Caspar Kalthoff, to study inventions and to make small-scale models for display to interested people. Sir Nicholas Crisp (*c* 1599–1666), who almost monopolized the lucrative trade to Guinea, was conspicuous for his interest in the arts and manufactures, giving very large rewards to inventors. He personally studied brick-making and devised a new method that was long used. In 1648 he put forward a scheme for the manufacture of copperas (ferrous sulphate), and introduced economies in the boiling-process. New inventions connected with water-mills, paper-mills, and powder-mills came into use through the knowledge he made available. Third was Samuel Hartlib, the son of a Polish father and English mother, who came to England about 1628 and initiated a kind of mercantile agency and information-exchange, afterwards taking part in many public questions of the day. He also had a plan to publish practical treatises on agriculture and the arts, such as the book by Gabriel Plattes on mines and minerals for prospectors and emigrants to the colonial plantations [7].

During the Civil War Hartlib looked into the possibility of founding a Baconian college, in which John Evelyn (1620–1706), William Petty (1623–97), and Robert Boyle (1627–91) were also interested. All had exceptional talents and the enthusiasm of youth. In 1647 Hartlib approached Boyle about Petty's proposal to found a college of tradesmen and produce a history of trades. A group of men sharing such ideas were then meeting at Gresham College, London, and the time seemed ripe for the venture. However, when Cromwell's army came into London in 1648–9 some of the group moved to Oxford, and before conditions had returned to normal the plan was abandoned.

Nevertheless Petty, the son of a Hampshire clothier, had collected information about textiles and dyeing, and Boyle and Evelyn devoted much time and thought to trade receipts and processes. On the restoration of the monarchy and the foundation of the Royal Society in 1660, many papers on such subjects were read; they were subsequently preserved in the Society's archives.

Several members showed their approval of these inquiries by drawing up lists of manufactures and trades that should be studied. Such drafts were produced independently by Petty, Evelyn, Christopher Merret or Merrett (who translated Neri's *L'Arte vetraria* (p 217)), and Robert Hooke. Of these, Hooke's was the most comprehensive and systematic, and his first item was the 'History of Chymists, either such as make Tryals on Metals, or operate on Mineral, Vegetable, or Animal Substances'. In his manuscript papers Hooke made it clear that he considered the Society's two prime objects to be the improvement of natural knowledge, arts, and manufactures by experiments, and the rediscovery of lost arts and inventions.

Boyle expounded his views on these matters in his essays on the 'Usefulness of Experimental Natural Philosophy' (1663, 1671), and, like Hooke, thought that science and the manufactures both stood to gain from closer contact. Boyle obtained a good deal of information from conversations with craftsmen, and was convinced that much empirical knowledge could thus be collected and used in the development of chemistry as a science. For example, illustrations taken from iron-making, goldsmiths' work, glass-making, soap-boiling, and other similar occupations were used to good effect in his 'Sceptical Chymist' (1661). At about the same time, Otto Tachenius (*c* 1620–1700), a German chemist who settled at Venice, was among the first to regard salts as formed from acids and alkalis, and he derived his strongest arguments from the practices of glass-makers, soap-boilers, and the like [8].

Books and periodicals assisted the spread of information on the arts and trades that had been brought together during the 1660s. Much of this was published from 1665 in the 'Philosophical Transactions' and in Sprat's 'History of the Royal Society' (1667). John Houghton's collections for the improvement of husbandry and trade (1681–3 and 1692–1703) also helped, for Houghton had the Royal Society's approval and made good use of their material. These news-sheets, he said, were intended to benefit 'not only the Theorical Gentleman, but also the Practical Rustic'. In addition, the first comprehensive dictionaries that set out to include technical information began to appear during this period, such as J. J. Hofmann's *Lexicon universale* (1677) and supplement (1683), T. Corneille's *Dictionnaire des arts et des sciences* (1694), and John Harris's celebrated *Lexicon technicum* (1704).

There were other movements in the chemical field on the continent, and the very influential writings of such men as Glaser (d *c* 1671), Glauber (1604–68), and Lémery (1645–1715) often cast light upon certain processes in the arts; but they also illustrate the close connexion of chemistry with pharmacy and medicine during this period. The works of Becher (1625–82) and Kunckel (*c* 1630–1703), Boyle's most eminent continental contemporaries, contained numerous ideas and observations that were intended for application in the technological field. Both were given to alchemical pursuits, and both were associated with numerous commercial or economic projects, most of which failed. Of the two, Kunckel was the better practical observer, and, like Boyle, made numerous contributions to such arts as engraving, tinning, gilding, varnishing, and glass-making. He spent the years 1679–88 at Berlin in the service of the Elector Frederick William (1640–88) as director of his laboratory and superintendent of the glass-works. His *Ars vitraria experimentalis*, which included the work of Neri and Merret, was published in 1679 (p 222).

In Sweden also the importance of chemistry in the arts was recognized, no doubt through German influence. Attempts were made during the reign of Charles XI to exploit the natural resources of the region with the aid of chemistry. In 1683 the king had a technological laboratory built, which was superintended by Urban Hjärne (1641–1724), assessor and later president of the *Bergcollegiums* in Stockholm. Ores, minerals, soils, and so forth were examined there, and attempts were made to find uses for the various chemical products that could be obtained from them. Charles XI invited Kunckel to Stockholm and created him Baron Löwenstjern in 1693.

One very important result of the widespread study of many manufacturing processes by men of science was the growth of knowledge of ways of testing materials, and this had a considerable effect on the development of chemical analysis. Here Boyle, as well as Kunckel and Homberg (1652–1715), made valuable contributions.

A growing confidence in the experimental method and its beneficent influence on technology was manifested during the second half of the seventeenth century. As Sprat said: 'The genius of experimenting is so much dispersed that . . . all places and corners are busy and warm about this work.' And again: 'This desire of glory, and to be counted Authors [inventors, discoverers], prevails on all, even on many of the dark and reserved Chymists themselves.' In such an atmosphere few important technical discoveries remained hidden for long.

H. de Blancourt admitted that in technological work most improvements resulted from chance observations by men seeking something they could not find. Such discoveries were made, we might say, by 'hazard of Art', for fruitful accidents are fruitful only because those to whom they happen have the knowledge or skill to profit from them. This newly won confidence, however, amounted to a belief that scientific principles could be applied to a great variety of problems. As de Blancourt put it, for those who 'set themselves thoroughly to study the true principles of whatever they undertake, it is not difficult to retrieve lost Arts'.

In the remainder of this chapter selected processes that best seem to characterize the period will be described in greater detail.

III. CHEMICAL INDUSTRIES USING WOOD

Wood, as a source of charcoal, tar, pitch, resin, potash, turpentine, lamp-black, and printers' black, all widely used materials, will be considered first. The favourite trees for these purposes were oak, beech, alder, fir, and pine in the northern countries, and similar processes were employed from the Mediterranean to Norway, from Greece to New England.

In northern Europe three kinds of charcoal (vol II, pp 359, 369) were required, the first, for use in iron-works, being often made from oak and beech. The wood, cut into 3-ft lengths and cleft if necessary to a suitable size, was stacked triangularly about a central pole, smaller pieces being placed around them until the base of the heap was as much as 20 to 30 ft in diameter, the whole being covered with turf, loam, or clay (figure 416). Vent-holes or 'Registers (as our *Chymists* would name them)' were made in the stack with the handles of long-toothed rakes. The central pole was then removed and the 'coaling' begun by building up a fire with burning charcoal added through the central hole. Afterwards the 'coal' was raked into wains, the larger and grosser pieces being taken to the forges, the medium and smoother pieces being sacked by the 'colliers' and taken to the towns. Any 'charked' (charred) roots were reserved 'for *Chymical* fires, and where a lasting, and extraordinary *blast* is required'.

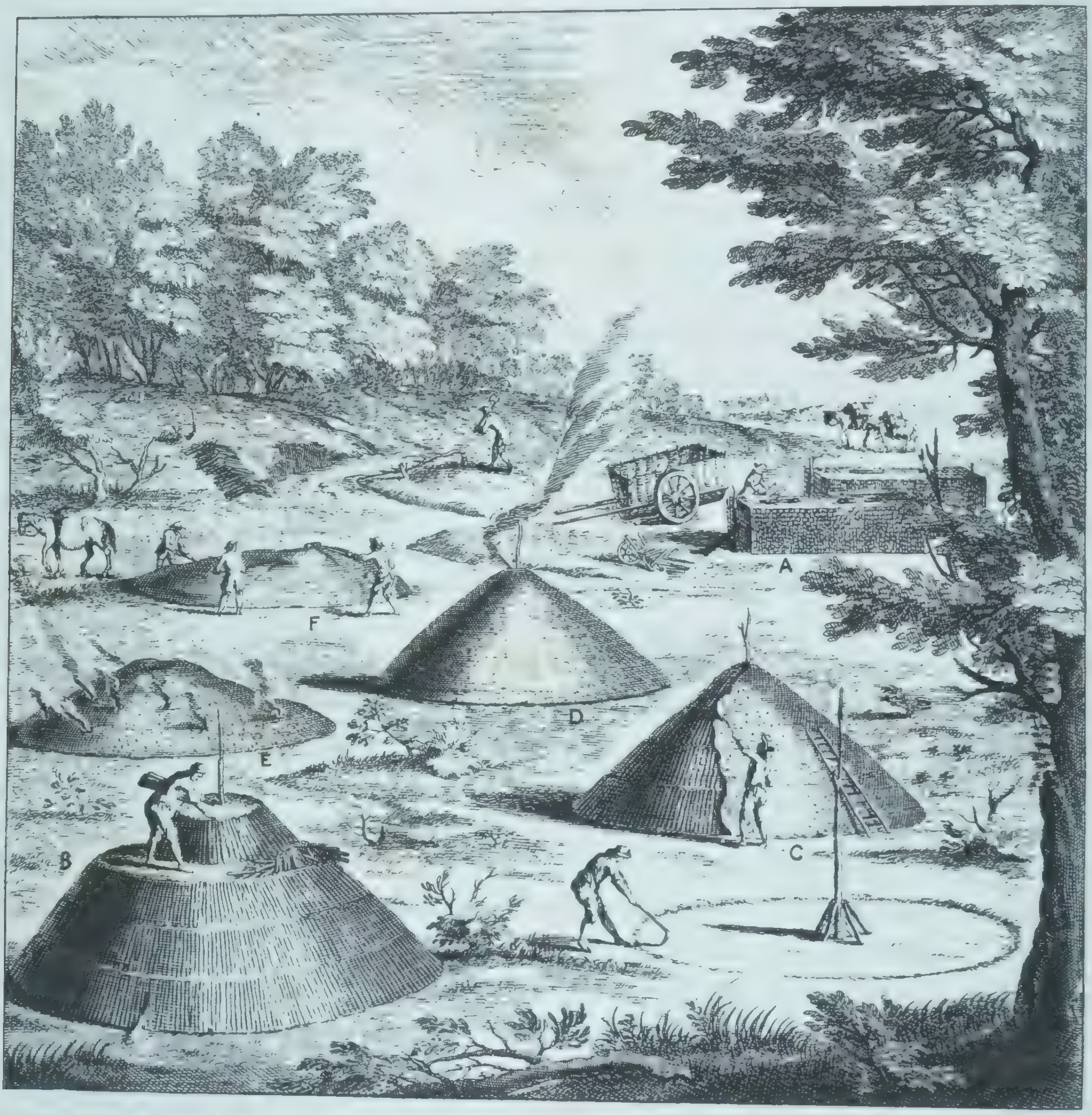

FIGURE 416—*Charcoal-burning.* A, *wood-stack;* B, *preparing the heap of wood;* C, *covering it;* D, *a freshly-lit, and* E, *a nearly burnt-out heap;* F, *uncovering a carbonized heap.*

The second type of charcoal, for use in the gunpowder-mills, was made from alder-wood stripped of its bark and stacked in heaps large enough to provide 60 sacks of 'coal' each. Such charcoal was found to grind best for use in gunpowder. The third kind was made from brushwood and small coppice-wood, which was burnt in the open, the fire being controlled by throwing on water with scoops filled from large tubs standing nearby. This was accounted superior kindling-charcoal and was required in large towns.

Fir and pine were needed especially for the manufacture of tar, pitch, and resin, used as preservatives particularly for timber and ropes and consequently in great demand for shipping. Pieces of wood—the knotty parts of fallen pitch-pine were favoured in heavily wooded areas—of a convenient size were stacked on a hearth built above the ground so that a receiving vessel could be placed underneath, the hearth being shaped somewhat like a shallow funnel ending in a gullet. The wood was then covered with loam or clay and the same procedure followed as for charcoal-making. John Winthrop, who described the process for the Royal Society, pointed out that this was a crude form of distillation *per descensum*, and that it could be done equally well in furnaces (retorts). Though such a furnace—the 'beehive', a simple adaptation of the charcoal-burner's mound—was described by Glauber in 1657, it seems not to have been much used for this purpose, probably because it appeared to be an unnecessary expense (figure 417). When all the tar had run out the remaining charcoal was reserved for the smiths, who preferred this and sea-coal (ordinary coal) to other fuels. Pitch was made by the simple process of boiling the tar until a sample on cooling showed the required consistency. This process, it was found, could be speeded up by adding resin, whereas ship's carpenters sometimes merely heated the tar in an iron kettle, ignited it, and, when the tar had thickened sufficiently, extinguished the fire by covering the kettle.

For resin, the knotty parts of pine were split into thin small pieces and boiled in water, the turpentine gradually thickening and becoming hard on cooling. Tar, pitch, and resin, especially the last of these, were often burnt in a sheltered spot and the soot collected on rags for lamp-black and printer's black.

The use of wood, particularly oak, and of various plants for making potash and soda, will be indicated later, in connexion with glass-making and soap-boiling.

IV. SUBSTITUTES FOR WOOD

During the sixteenth century the widespread consumption of wood for all such purposes created a shortage of timber suitable for ship-building, and this made restrictions imperative. Where coal was abundant, as in parts of England and Wales, attempts were soon made to use it in place of charcoal (ch 3). By 1600 it had been tried in several trades where the presence of acid sulphureous fumes had no deleterious effect, and it had also been used experimentally in Wales for the preliminary roasting of ores. By 1610 coal was sometimes employed as fuel in brick-making, brewing, dyeing, and brass-foundry work. It was also pointed out at this time that coal would be equally satisfactory in boiling and extractive processes, for making copperas, alum, saltpetre, sugar, resin, gum, turpentine, wax, tallow and soap, vegetable oils, and distilled waters. From then on, the use of coal became widespread. Not many years later the coal used by the brewers, dyers, soap-makers, salt-boilers, and lime-burners of Westminster was creating so much smoke that it penetrated even into the Palace of Whitehall, as John Evelyn tells us in his diary (p 77).

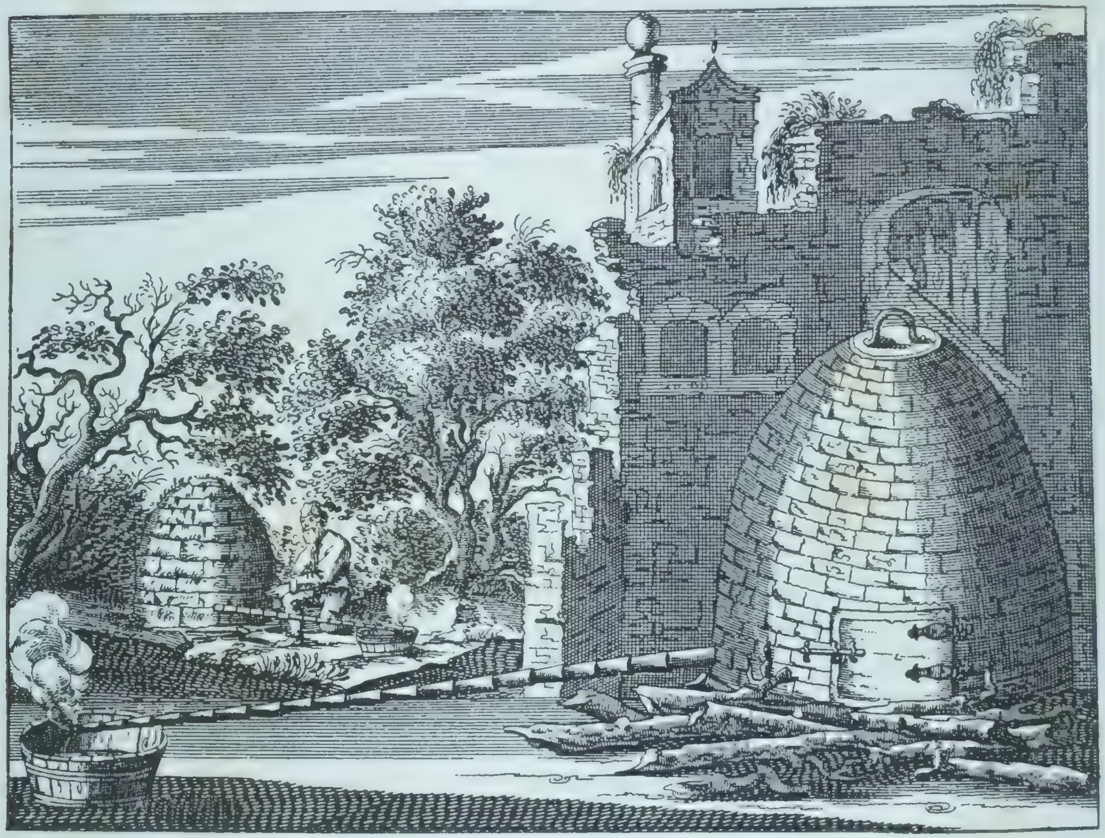

FIGURE 417—*Glauber's 'beehive' furnace, and method of collecting wood-tar. 1657.*

Another approach to the same problem was to economize in fuel. Thus Sir Nicholas Crisp, in Commonwealth times, noted that much was wasted during the concentration of liquids, since it was the practice to pour the cold, weak solution into the tank containing the hot concentrated liquor; he recommended that the steam and waste heat from the latter should be used to warm the weaker solution, which could then be allowed to trickle in without interrupting the boiling. Another help was the inclusion of the fire in a grate surrounded by brick-work, which seems to have been more widely adopted during the latter part of the seventeenth century and enabled some trades previously conducted in the open air to be practised within doors. Fairly early in the next century further improvements in design were suggested; for instance, John Allen or Alleyn (1660?–1741), a Somerset physician and a friend of Newcomen, patented ways of using the hot furnace-gases more effectively and of insulating the boiling-tanks.

Meanwhile various spectacular advances in the use of steam, such as the water-raising machine of Savery and Papin's 'digestor' (a forerunner of the autoclave), caused some technologists to look upon steam-heating as of possible use for chemical extractive processes. Desaguliers (1683–1744) and his associates worked out a method about 1720, which showed how useful steam would be for the better control of heating during distillation; for maintaining dyeing-vats at any required temperature; for obviating the very thick and consequently expensive bottoms to boilers used in sugar-refining (figure 4) and soap-boiling, as well as for salt-boiling (during which the bottoms were frequently burnt out) (vol II, figure 324); for the tallow-chandlers, who would welcome a vessel in which steam could mix with the crude tallow; and for reducing hazards in trades where it was necessary to boil such inflammable substances as turpentine, varnishes, and oils. However, from Desaguliers's plan it is evident that much more experience in the manipulation of steam was needed before such projects could be turned to practical use (figure 418).

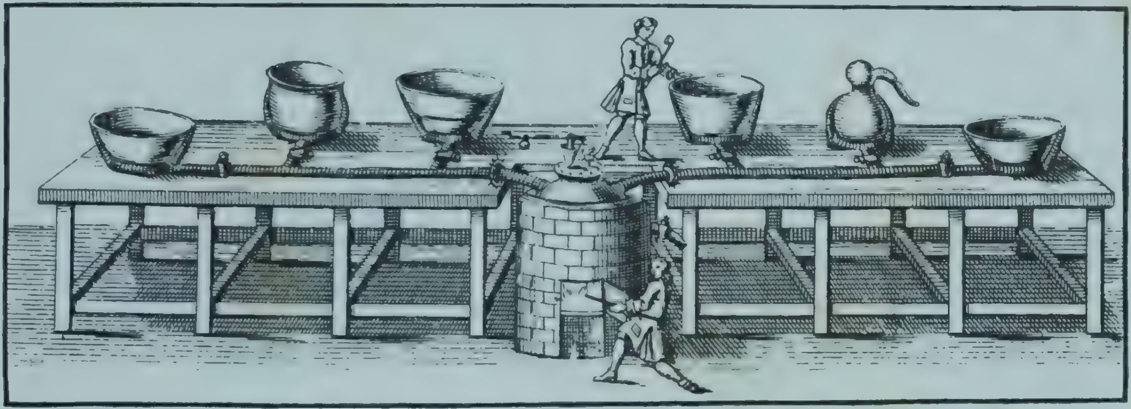

FIGURE 418—*Desaguliers's scheme for heating boilers, stills, and so forth from a steam boiler.* c *1720.*

Among the results of the search for substitutes for wood must be mentioned a unique and successful venture, in which shale was used for the production of 'Oil of Petre' or mineral turpentine, as well as of tar and pitch, first described in

1697 and still being produced as 'British Oil' in the second half of the following century. This was carried out in the neighbourhood of Broseley and Pitchford, near Wenlock in Shropshire (figure 419). The patentee, Martin Eele, collected the bituminous shale found lying over the coal and ground it in horse-mills like those used to grind calcined flints for glass-making. Some was taken to the still-house for the production of oil by distillation, and the rest was boiled with water in large coppers, the bituminous matter separating from it and floating. This was removed and evaporated until it had the consistency of pitch, when part of it was mixed with the oil already prepared until it had been thinned to the consistency of tar. Eele's pitch and tar were found useful on ships, as they did not crack like wood-pitch and tar but remained relatively soft in use. They were sent by boat down the Severn to Worcester, Gloucester, and Bristol.

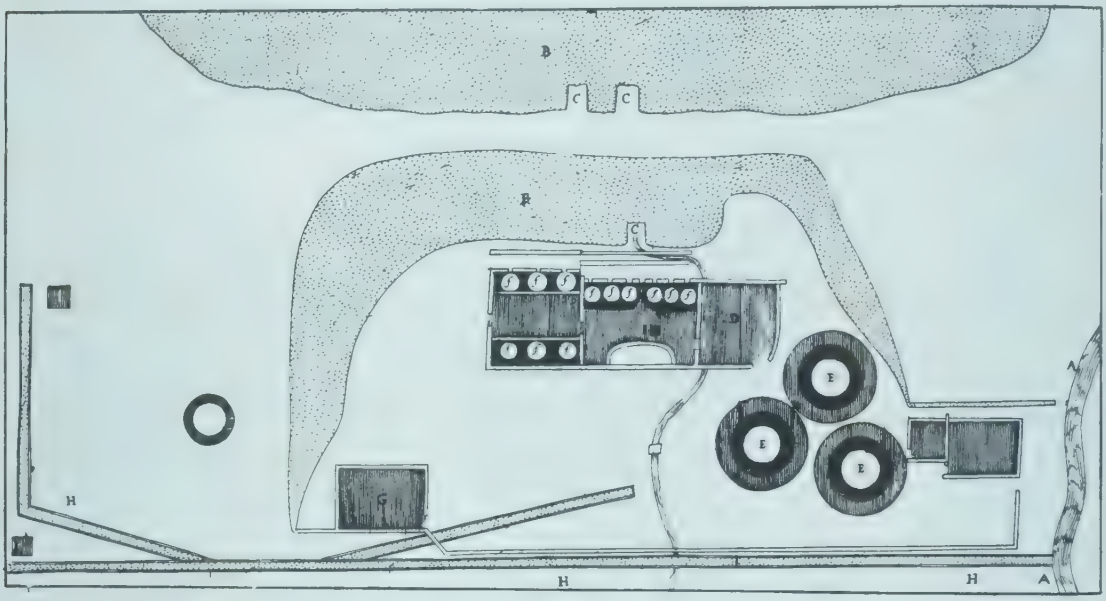

FIGURE 419—*Plant for manufacturing 'oil of petre'.* (A A) *The river Severn;* (B, B) *hills or rocks 'where are coal-pits';* (C, C, C) *the pits whence the stones are taken;* (D) *the storehouse;* (E, E, E) *horse-mills for grinding stones to powder;* (f, f, f) *coppers in which the material is boiled to separate the bituminous material from the stone;* (G) *still-house for distilling the oil;* (H, H) *roads;* (I) *well.*

Somewhat similar experiments carried out at this time by Thomas Allgood in the Pontypool (Monmouthshire) area resulted in the production of black varnishes that acquired a high lustre after long stoving. These were applied to sheet iron, copper, and tinplate goods, thus ushering in the 'Welsh' lacquer manufacture during the early decades of the eighteenth century.

In the Broseley area further work on the use of coal for roasting iron ore in heaps consisting of alternate layers of ironstone and coal, and on 'charking' coal in mounds resembling those of the charcoal-burners, began probably in the first two decades of that century. These became of considerable importance in the hands of the Darby family (p 80). But the vital progress in this field belongs to a later period, when the coke-oven and the blast-furnace revolutionized iron manufacture. For a considerable part of the century the high sulphur-content rendered coke-iron too brittle to work successfully under the hammer, and it was generally mixed with soft grades of iron before being considered fit for use.

V. MANUFACTURE OF TINPLATE

Another notable advance in the metallurgical field was the British method of production of tinplate, introduced towards the end of this period (figures 420, 421). Early in the sixteenth century the only source of tinned sheet iron was Germany, where it was made on the borders of Saxony and Bohemia by a traditional method. Lengths of bar iron were beaten into sheets under the tilt-hammer, after which scale was removed by long soaking in tubs containing fermented rye-meal infusions of various strengths, the sheets then being rubbed with sand, or filed, and dipped in molten tin covered with grease. In time of war, however, supplies were interrupted and serious attempts were made, particularly in Britain, Sweden, and France, in the 1620s and again in the 1660s, to use home-produced iron and Cornish tin for this purpose. They met with no success, except a partial one in France, where, under Colbert's instructions, a number of Bohemian tinmen and hammermen were enticed to a factory in Nivernais (now the Département de la Nièvre). Here, for a time, by copying the Bohemian process they produced sufficient tinplate to meet the navy's requirements of food-containers and utensils of various kinds. But it was not until the 1720s, some years after Réaumur's inspection of French methods and shortly after his study of the chemical problem of de-scaling, that the French manufacture reached a satisfactory state.

By 1730, however, superior machine-rolled tinplates were being made at Pontypool, a new technological process having been worked out by John Hanbury and his assistant Edward Allgood (p 697). Red-hot bar iron was rolled in several stages to make plates of various thicknesses, this part of the process having been in operation by 1697. It appears that the subsequent stages of de-scaling, annealing, tinning, listing, and cold-rolling were not completely worked out for several years after this. A description of the method as practised somewhat later in Yorkshire shows that great care was taken to avoid the production on heating of black scale (which was far more difficult to remove than the red). As the sheet iron came from the rolls it was steeped in a solution of sal ammoniac to remove most of the scale, and subsequently the plates were allowed to stand for some time before tinning in an acid infusion of bran and water (2 bushels to 100 gallons). They were then rinsed, dipped in molten tin covered with train-oil (whale-oil) and resin, and their thick lower edges of surplus tin removed by dipping (listing) in a small quantity of molten tin and wiping with a thumb-guard. Irregularities left after handling through a number of stages were evened out by cold-rolling.

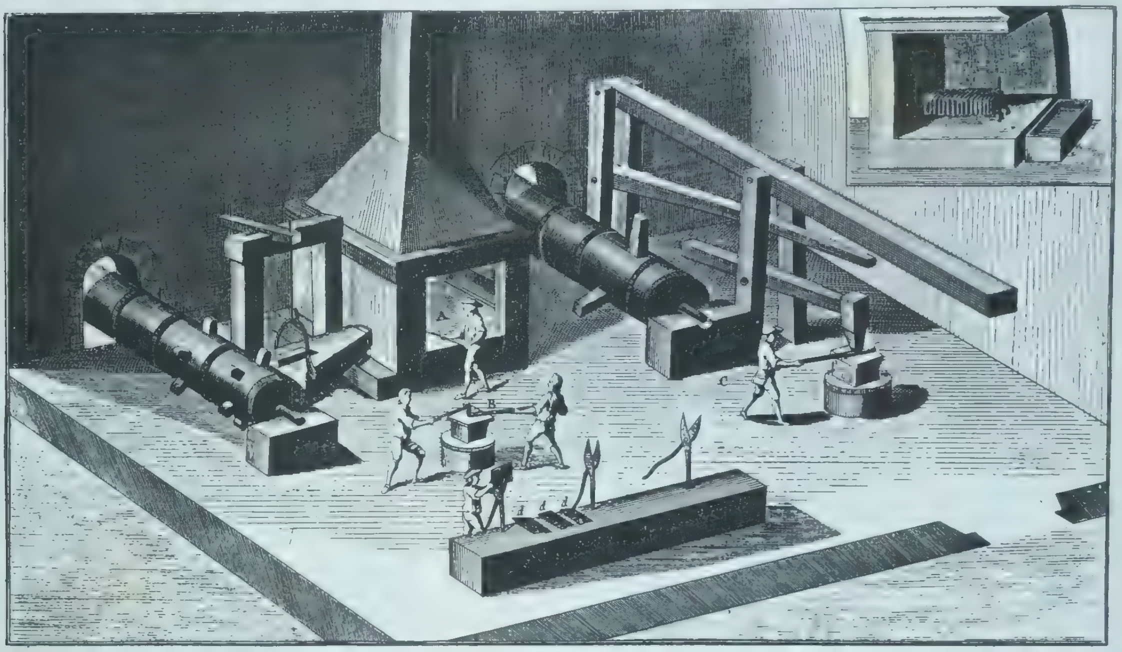

FIGURE 420—*Manufacture of tinplate* (I). (A) *Heating bar iron at a forge with water-driven bellows,* (B) *extending bars by hand-hammering, or at* (C) *by water-powered hammer.* (d, d, d) *Partly extended plates. The extension was continued by long heating and hammering of a stack of plates* (inset).

VI. MANUFACTURE OF ZINC

Another important and characteristic development of the period was the introduction of metallic zinc. This metal, whose name seems to have been coined by Paracelsus (1493?–1541), was scarcely known until the early seventeenth century, although the name *counterfeht* given to calamine refers to the early use of that ore with copper to make brass, that is, for giving copper the colour of gold (p 37). Because of this property, calamine and zinc itself were for long in great demand by alchemists. During the seventeenth century most of the zinc used was imported by the Dutch from China and the East Indies, and was at first known to them as Indian 'tin' or pewter, whence the English 'spelter'. The silvery appearance of much pewter and tinplate ware after this time appears to have been due to the admixture of a small proportion of zinc with the tin used in both.

The earliest description of the smelting of zinc direct from the ore is said to be that given in the Chinese metallurgical work *T'ien kung k'ai wu* of 1637; the method was essentially different from that at first developed in Europe. The mineral, presumably mixed with powdered charcoal, was put into earthen pots, which were dried slowly after tight luting. The pots and cakes of charcoal were stacked in alternate layers over wood and the pile was fired to attain a red heat. At the end of the process the pots were broken, the solid masses were removed, and the metal was re-fused and cast into large oblong cakes, in which form it was exported.

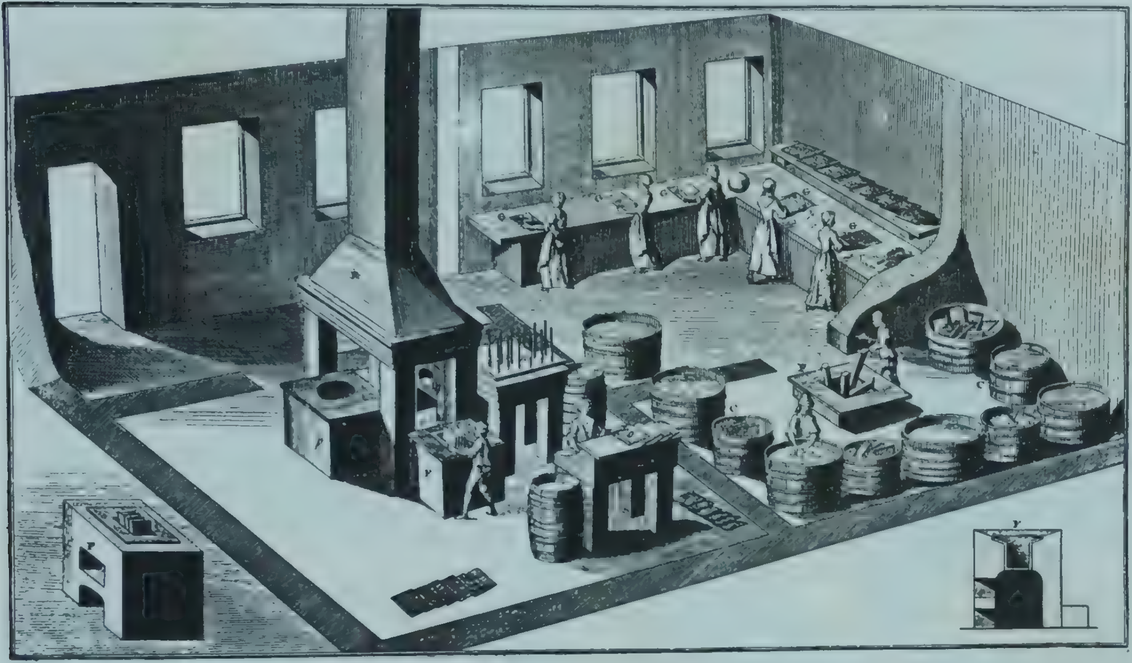

FIGURE 421—*Manufacture of tinplate* (II). *The plates, roughly cleaned on a grindstone, soak for 24 hours in a solution of fermented rye to remove scale* (C). *They are then cleaned by the women at* (G) *and placed in tubs of water. At* (F) *the plates are dipped in molten tin (covered with tallow to prevent oxidation), first in stacks and then individually. They cool in the rack* (N.)

Zinc was already associated in the time of Agricola with the mining town of Goslar, west of Halberstadt. A description of 1617 shows that it was regarded as an almost valueless by-product produced during the smelting of silver and lead ores: 'There is formed under the furnace, in the crevices of the walls, where it is not well plastered, a metal which is called zinc or *counterfeht*, and when the walls are scraped the metal falls down into a trough to receive it' [9]. At first it was not much used except by alchemists, but it was known that it made tin more beautiful and that it could be mixed with copper to make brass and other alloys, such as that afterwards known as prince's-metal (pp 30, 37, 51).

The gradual realization of the general usefulness of zinc, however, led to a better method of extraction at Goslar by the early years of the eighteenth century, judging by the first-hand description of the process by Neumann, who pointed out that the metal was obtained not from a zinc ore found at Goslar but from the lead and silver ores of Rammelsberg. During the smelting, zinc vaporized and passed into reservoirs made for the purpose in the front wall of the furnace above the gutter by which the lead was run off. These reservoirs were almost enclosed on the inside by a large flat stone, small chinks being left for the vapour to enter, and by another tightly luted stone on the outside. Throughout the 20-hour fusion the outer parts of these receivers were sprinkled frequently with cold water to cool and condense the fumes. Afterwards the outer stone was hit with an iron rod to loosen the luting, whereupon the molten zinc ran out like mercury. The German zinc was remelted in an iron pot and cast in hemispherical masses. By this time the principles of the process were more clearly understood, and it was realized that the successful extraction of zinc from its ores would depend primarily upon the design of the receivers and on an effective method for condensing the metallic vapour. With this knowledge it became possible, just after the period here considered, to attempt the smelting of zinc direct from calamine.

VII. DYEING AND COLOURING

Another aspect of the search for brighter finishes and livelier colours is shown by developments in dyeing, which has always been regarded as a chemical art. Petty in 1662 made the connexion clear by mentioning in his outline of dyeing such techniques as colouring iron and copper wares black with oil, the varnishing of silver foil to emulate gold, the production of coloured enamels, tinning iron with block tin and sal ammoniac, converting copper with calamine into brass 'and with Zinck or Spelter into Gold', that is, to a golden colour [10].

At this time the favourite dyes were madder, kermes, and cochineal (reds), woad, indigo, and logwood (blues), archil or *oricello* (purple), weld, wood-wax, and 'old fustic' (yellows). Great difficulty was experienced in dyeing a fast green. Petty noted that no simple green dye had in his time come into general use, and the position remained unchanged for another century. The best was 'sap green', obtained particularly by country people from unripe buckthorn (*Rhamnus catharticus* L) berries crushed in water, the infusion being evaporated to the consistency of honey. Otherwise, textiles were first dyed blue and then yellow, or vice versa.

By 1500 instructions for cultivating madder (*Rubia tinctoria*) had been published in Holland, and for the next 300 years the Dutch (Flemish) retained their position as the most advanced growers in the world, meeting little competition until the beginning of the eighteenth century when the plant was much grown in parts of France. The use of alum as a mordant for wool, as also for producing the much-favoured Turkey-red colour on cotton, was essential. After dyeing, the articles were immersed in bran-water, the starch of which, according to Petty, helped to fix the colour.

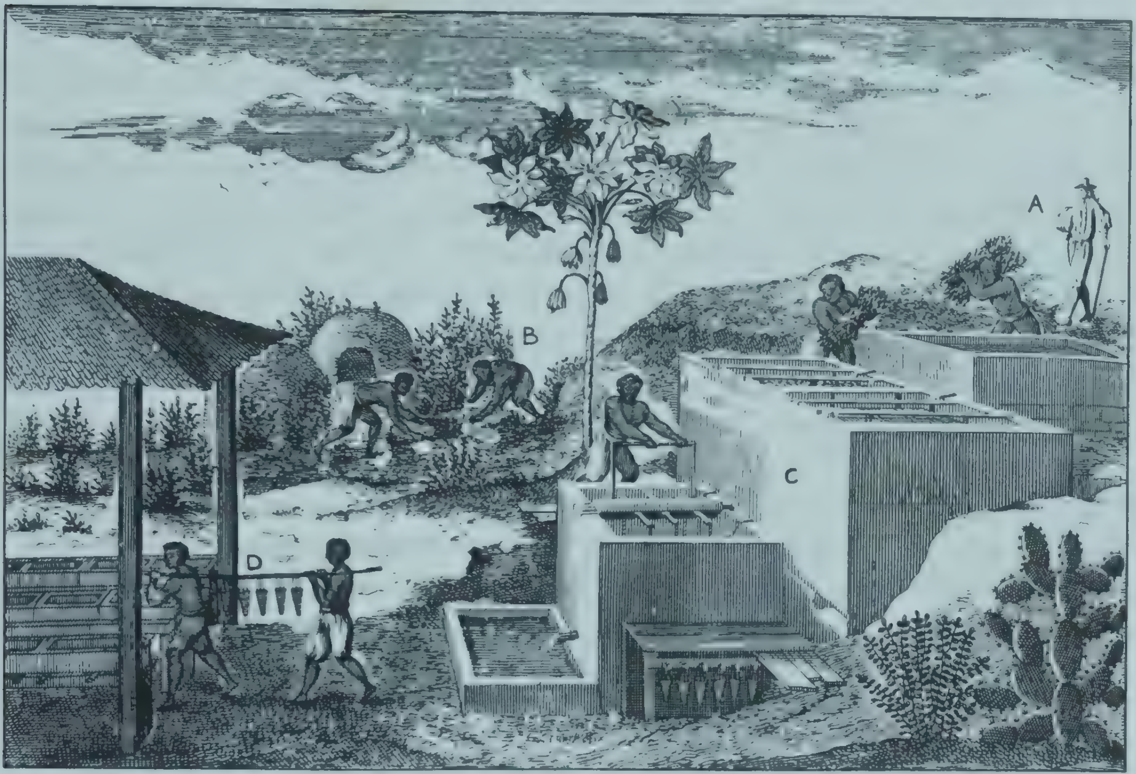

FIGURE 422—*Tropical indigo manufactory. 1694.* (A) *The white overseer;* (B) *cutting the indigo-plant;* (C) *infusing it in water;* (D) *carrying away the dye.*

The Dutch imported indigo direct from India, whence they had obtained it since about the fourteenth century. Its production was not well understood, however (figure 422). After 1600 larger quantities were brought to Europe by sea, and it was sometimes known as 'blue ynde' or 'devil's dye'. During the seventeenth century woad (*Isatis tinctoria*) was still widely used as an alternative, or even in preference, as it could produce a variety of shades from light blues to damson.[1] A scale was used to compute the ingredients necessary to produce any required shade. Logwood, like most woods that yield dyes, was chopped and ground before use, and the fabrics were boiled with the dye in rain- or river-water for as long as necessary. This made it unsuitable for wool and for articles that would suffer damage by such treatment. Woad and indigo were popular as they required no alum or other mordant; in fact, Petty stated that alum was not then used with either (vol II, pp 364–5).

Though safflower (*Carthamus tinctorius*) and turmeric (from Indian species of *Curcuma*) are sometimes thought of as the yellow dyes of this period, they had largely been superseded, at least in England, by weld or dyer's rocket (*Reseda luteola* L), much grown in Kent for the London dyers, wood-wax or dyer's greenweed (*Genista tinctoria*), and the misleadingly named 'old fustic' (*Chlorophora tinctoria*), from the West Indies and tropical America. Weld was set with potash to give a deep lemon colour, and wood-wax with potash or urine to give a similar result. Shades as light as straw could be obtained with old fustic used with slaked lime. Safflower gave orange shades with alkalis.

Other plant dyes for which there was some demand included brasil and annatto (or arnotto). Brasil was chopped and ground and used with alum for reds; potash was also added for purples. Annatto, from the tropical American tree *Bixa orellana*, was later known as a yellow-brown dye, but an early variety gave an orange colour when used with potash on silk, linen, and cotton. 'Young fustic' (Venetian sumach) which is not less ancient that the 'old fustic', was also used similarly for orange shades.

Lichens, as well as larger plants, were brought into service. Archil, from species of *Roccella* and *Lecanora*, was imported to Florence from the Near East, and for a considerable time the European trade in it was a monopoly of the Italians. English, Flemish, and German cloth-merchants and dyers were forced to buy it from them in the form of *oricello* dye-paste. Archil lichens were discovered on the Canary Islands in 1703, but even then could not be used until the formula for preparing the paste was divulged, so it is said, by a Florentine cloth-dyer working in London. The powdered dried plant was mixed with stale urine and lime and used with alum for dyeing silk and wool in violet shades. Some other lichens were also used in England and Flanders.

There were several methods for dyeing black, but the most common and perhaps the most successful was to use a solution of copperas (p 680) with added galls, oak-bark, or sawdust. A large amount of copperas was used for this purpose.

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[1] Woad and indigo plants both yield the same dyestuff, indigo or indigotin ($C_{16}H_{10}N_2O_2$).

Insect dyes (vol II, p 366), such as kermes (*Coccus ilicis*), from Anatolia, and cochineal (*Coccus cacti*), were also in demand, particularly the latter, obtained from Spanish America and named after the Spanish word *cochinilla*. Spain organized its collection under Cortez in the first half of the sixteenth century, and it gradually displaced kermes. The cochineal-culture was centred in Mexico for nearly 400 years until rendered unprofitable about 1880 by the advent of synthetic dyes.

The use of cochineal, by itself somewhat uninspiring though producing attractive 'incarnadines' (pinks) with lemon-juice, received a great stimulus when it was discovered that pewter in *aqua fortis* (nitric acid) turned the red dye into a bright scarlet (p 679). Petty called it a change from 'red rose-crimson to flame colour'. Cornelius Drebbel and his sons-in-law, the Kuffler brothers, developed the process and used it first at Stratford (Bow). The Kufflers' dyeworks dates back to 1607, and cochineal scarlet ('Bow dye' or 'the new scarlet') was already becoming known in the 1620s. The solution was made by dissolving bars of pewter in *aqua fortis*, and the dyeing-kettles were also of pewter. It seems that the effect was ascribed to the *aqua fortis* rather than to the tin of the pewter, for one consequence was that saltpetre (the source of *aqua fortis*) was used by some dyers in an attempt to brighten other colours, by a process of 'back-boiling', though argol (tartar deposited from fermented wines) was also commonly employed to the same end [10].

The Kufflers did not form a company to commercialize their discovery till about 1635. By 1647 Jacob Kuffler was dyeing scarlet in Leiden, the method having been introduced there about 1620 by Van der Heyden, and other members of the Kuffler family formed a company about 1654 to use the process near Arnhem. Abraham Kuffler remained at Bow, and in 1656 Johannes Kuffler left Holland to take over the works. Shortly after 1660 the process was introduced to France at the celebrated *Maison des Gobelins* by Jean Gluck, who is thought to have obtained the method from Gilles Kuffler in Amsterdam. The discovery, which created a deep impression, was regarded as an outstanding achievement.

Further details concerning vegetable and insect dyes are given in vol V, ch 12.

VIII. VARNISHING, JAPANNING, AND LACQUERING

As already noted, dyeing suggested more than the colouring of textiles and in its widest sense the term was sometimes applied to the colouring of metal or wooden objects with varnishes and enamels. The latter, in turn, linked up with the manufacture of glass and glazed pottery, a field where technology and art meet. As in dyeing, so in varnishing and lacquering; a great deal of experiment was carried out with new materials, and from it new methods emerged. Varnishes to protect leather (vol II, figure 146), paintings, and woodwork had been made for a considerable time from drying-oils (turpentine or boiled linseed-oil) mixed with gums or resin and occasionally with colouring-matter. However, the lacquered wares of China, and, to a far less extent, of Japan, were imported in ever-increasing quantities during the seventeenth century, and they showed the possibilities of brilliantly finished and artistically decorated goods of all kinds, from trinkets and snuff-boxes to bedsteads and coaches, to a degree then unknown in the west. The supply, particularly of the Japanese wares, remained far less than the demand, and between 1660 and 1675 the new trade of japanning arose, first in Paris, then in London, and soon afterwards in Holland and Germany. To these developments several men of science contributed, including Boyle, Evelyn, Lémery, and Kunckel.

In the Far East lacquer was prepared from the sap of the varnish-shrub (*Rhus vernicifera*) by a traditional process that remained a carefully guarded secret until the middle of the eighteenth century. The early European wares, on the other hand, though termed 'japan' and imitating goods that more frequently came from Amoy and later Canton in China, were decorated with varnishes based on Indian shellac (vol II, p 362) and other gums in spirit of wine or oils. Boyle directed attention to an account by the Dutch traveller Van Linschoten of the Indian method of lacquering with shellac, and he tested various mixtures of shellac with spirit of wine and colours, as well as yellow varnishes, to give silver foil the appearance of gold, for application either to metals or to leather. The celebrated 'English' varnish, giving the appearance of gold to silver foil used to decorate coaches (vol II, p 174), was later attributed to Evelyn.

Before japanning became common, the favourite decoration was the mottled finish known as 'tortoise-shell', generally produced on yellow, red, or silver grounds. For the yellow and red, ochre and vermilion were ground with a little oil and added to the varnish. The object was given four or five coats of this preparation, drying after each application. Two coats of clear varnish were applied, and the object was then clouded over with darker varnish containing ivory black and dragon's blood, a red resin obtained from the Malayan rattan palm, *Calamus draco*. After anything up to ten applications of thin, clear varnish to give body and transparency, the work was smoothed by rubbing with Dutch rushes and a little water, then polished with tripoli on a wet cloth and, after washing and drying, finished off with a little oil on a clean cloth. For tortoise-shell on a silver ground, the object was first primed with whiting and gum arabic to receive the silver leaf. After silvering, two coats of the purest varnish containing a little dragon's blood and gamboge were applied, giving a golden colour. The surface was then clouded over and finished in the same way as the others.

Such methods were useful on all kinds of furniture and wooden objects, and also for embossed work, in which portions of the surface were raised with a thick cream of whiting and strong gum-arabic water. Apart from this, however, there was a growing demand also for similar effects on metal-work, and here the techniques were not so satisfactory, mainly because the varnish was liable to flake, although high polishes could be obtained. Despite this apparent disadvantage, such methods were practised in France.

In other parts of Europe, those wishing to varnish metals, particularly to imitate the more severe black-and-gilt articles associated with Japan, avoided shellac and spirit of wine lacquers and any form of priming other than polishing the metal surface. For such purposes linseed-oil was boiled with a gum or resin in a glazed pot with cover, through which a broad-ended stick was passed for stirring. Before use, the varnish was strained through a linen bag pressed between boards or iron plates. Lamp-black was frequently added to the varnish for initial coats, and ivory black for final coats. Other ingredients, such as litharge, were added to assist the drying of linseed-oil, at first apparently in making gold size.

By the early eighteenth century the art of lacquering iron and copper with japans that would resist rough treatment, acids, heat, and spirit of wine had come into being. How or when it began is obscure, but the innovations were sometimes attributed to Kunckel and Boyle. Wooden articles were placed in a declining oven, that is, one losing its heat, so as to avoid spoiling the work while at the same time hardening the varnish. Metal objects, however, could be stoved for longer periods and at gradually increasing temperatures, and this was done by the Allgoods in Monmouthshire. According to Kunckel, linseed-oil was boiled with umber until it became very brown and thick. After straining, it was again boiled until it became like pitch. This material could be thinned with turpentine to give a black varnish in a hot stove, or could be laid over a vermilion ground for tortoise-shell. For ordinary black japan, the object could be covered over with drying-oil and, when nearly dry, stoved at sufficient heat to blacken it without blistering. Afterwards the heat could be augmented, and the longer it was maintained the stronger became the coating.

Several of those occupied with the chemical arts were also interested in the preparation of artists' colours from vegetable materials and of coloured enamels for potters and goldsmiths. Two methods are especially worthy of mention—preparing coloured lakes with alum, and the use of calcined lead and tin as a basis of enamels. The former is exemplified by the yellow lake obtained from broom flowers, though many others were similarly treated. Fresh blooms were first boiled with a strong lye of barilla (soda) (vol II, p 354). The remains of the flowers were then removed and the extract was concentrated by boiling in glazed earthen dishes, after which roche alum (vol II, p 368) was added to complete. The mixture was then emptied into a vessel of clean water, and after a time the yellow lake settled at the bottom. The liquid was decanted off, and the colour spread on pieces of white cloth on bricks in the shade to dry.

IX. ENAMELLING

By the seventeenth century jewellers' enamels were made by calcining together a quantity of lead and a slight excess by weight of tin, after which the calx was ground to a fine powder and repeatedly boiled in water and decanted until no more powder was carried away (plate 29). It was then dried and the whole process carried out again. After evaporation to dryness, the finer calx (*piombo accordato*) at the bottom was collected and added to the mixture of white sand and purified alkali used to make crystal glass. The ingredients were mixed well and heated in an earthen pot for ten hours. The frit was then powdered and kept dry. This preparation was used as the basis of coloured enamels, the most common colouring materials being *crocus martis* (anvil scale), calcined brass, zaffre or smalt (cobalt minerals), and manganese dioxide. The pigments, having been powdered, ground, and put through a fine sieve, were thoroughly mixed with the powdered frit and heated in white-glazed pots. After thorough fusion proofs were made on small white-enamelled plates kept for the purpose and placed in a small oven resembling a goldsmith's muffle-furnace (figure 33). The shade was then adjusted as necessary by adding more of the frit or more of the colouring-powder.

X. MANUFACTURE OF GLASS

Numerous recipes for making glass (ch 9) were collected by Neri in his classical book on this subject (1612) [11], which was used until after the middle of the eighteenth century, with some additions by successive English, German, and French translators such as Merret, Kunckel, and de Blancourt [12]. In these books one can see the change from recipe-collection to a search for principles and a more scientific approach to manufacturing problems. During this period the need for better-quality and more transparent glass became acutely felt, for, as Merret pointed out in 1662, glass was then required not only for drinking-vessels, bottles, dishes, sleek-stones for pressing linen, hour-glasses and household ornaments, beads, bracelets, and pendants, but for special purposes, particularly windows, lenses for microscopes and telescopes, glass apparatus for experiments (figure 373), burning-glasses, and triangular glasses (prisms) for studying optics (plate 30). Good glass was needed also to provide convex spectacles for the aged and concave for the purblind (near-sighted) as well as transparent eye-shields for engravers and jewellers. Towards the end of that century artificial eyes, coloured with fine threads of enamel, were being made.

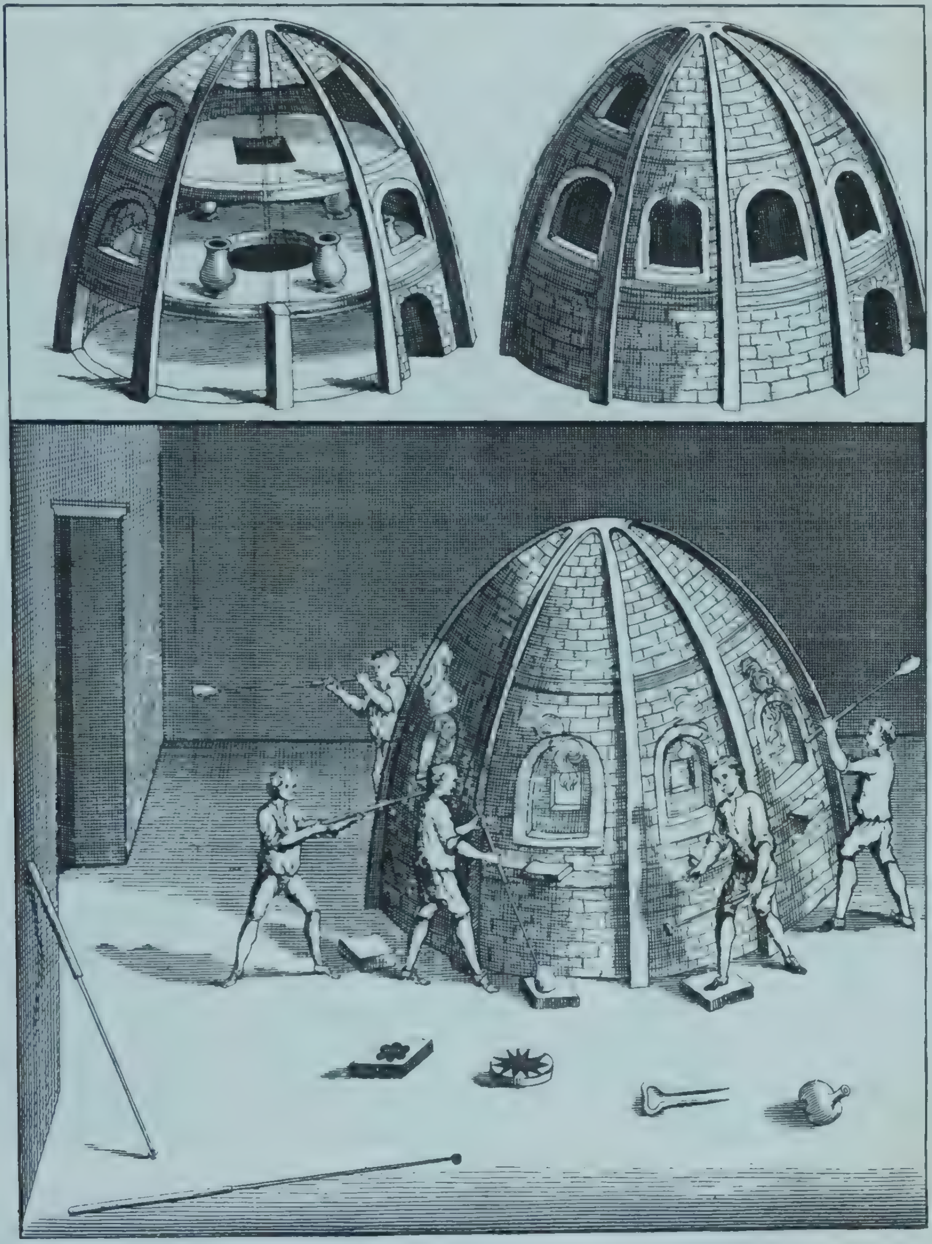

FIGURE 423—*The German glass-furnace. 1752.*

Three types of glass-furnace were recognized, the Italian, the Amsterdam, and the German (the last having been described by Agricola) (figures 423, 424). Of these the German was the most common and apparently the most convenient. This had two chambers above the fire, the lower generally having six openings through which the fusion in large pipe-clay pots was watched and 'metal' obtained for blowing; the upper chamber, which was cooler, served chiefly for annealing the finished wares. After being worked into shape by the master, the objects were often sheared from the pipe or cane and the remaining glass was broken off. The fragments were ground and returned to the pots for use in green glass.

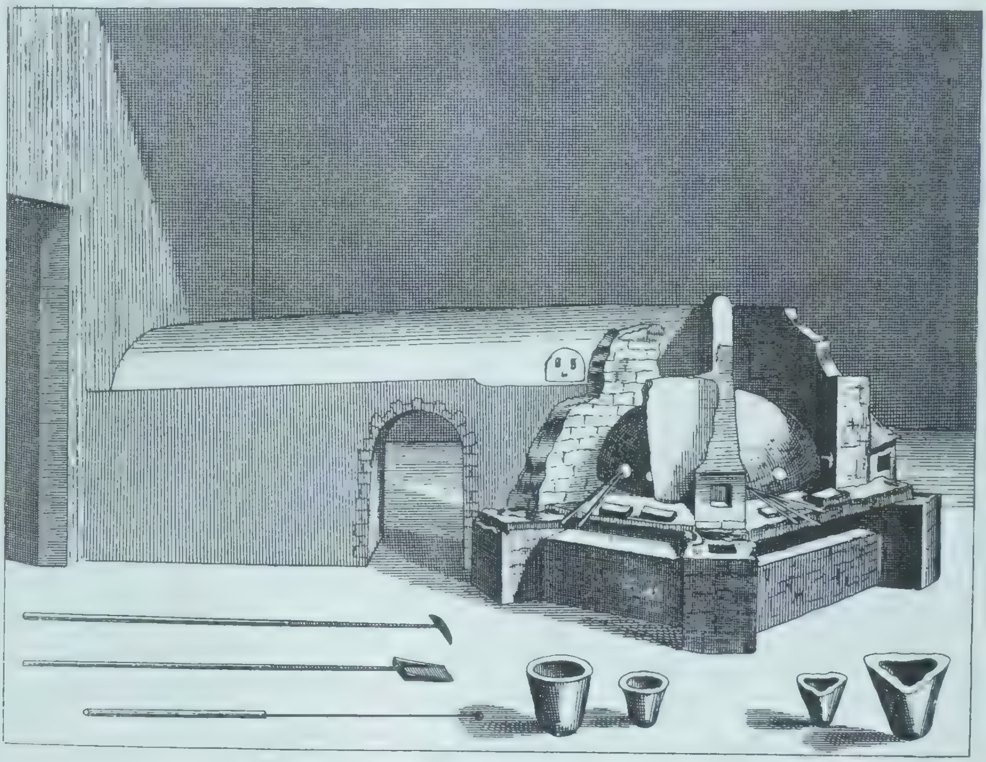

FIGURE 424—*The Amsterdam glass-furnace. 1752.*

The ingredients of glass were potash or soda, obtained from numerous locations and a great variety of plant sources and thus of various qualities (figure 425), and sand, under which heading were included the stones known to the German miners as quartz, the flints of English glass-makers, and generally any other stones that could be fairly readily powdered after calcination, provided they did not form a soft powder resembling lime. Allowing for all the possibilities of variations under these two heads, and for various colours, it appears that three main

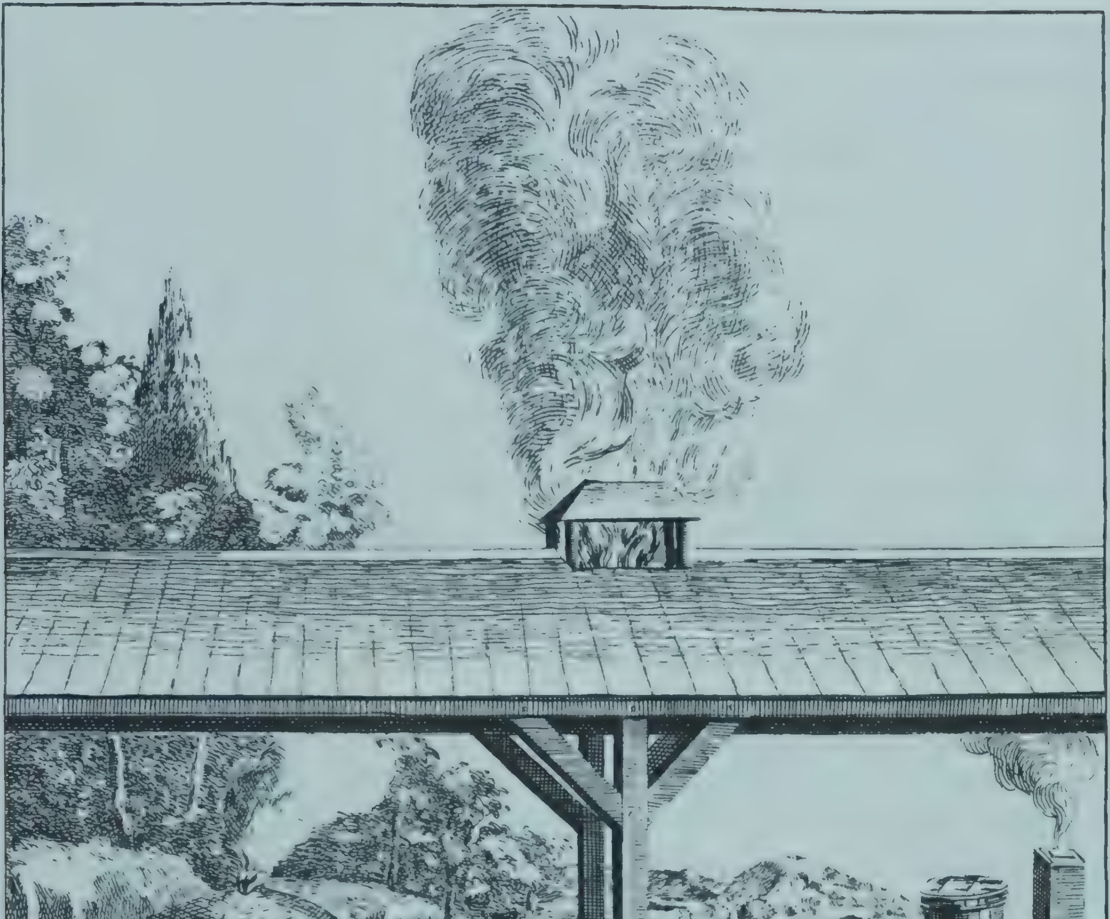

FIGURE 425—*The manufacture of potash.*

kinds of glass were produced, depending primarily on the purity of the materials. The coarsest, green glass, was made from ordinary sand (obtained by the London makers from Woolwich) and unleached ashes, to which were added scrap 'metal' such as ground cullets. On fusion the floating impurities (known as sandiver) were skimmed off, and sometimes the frit was thrown into water to free it from further impurities. The glass was then collected, ground, and re-fused. A better variety, white glass, was made from sand and the best-quality ashes, such as polverine imported from the Levant or barilla obtained from Spain. The resulting white glass, though scarcely transparent, and blue-tinged if made from the Spanish ashes, did not require water-treatment. Special varieties, such as crystal- or flint-glass, were made only with the best materials. Thus in the mid-seventeenth century the London makers used 'salt of polverine' or purified barilla (that is, the alkali obtained by leaching the best ashes, filtering and evaporating, drying and calcining, and finally grinding to powder) mixed with the best white sand (obtained from Maidstone) or with pulverized calcined flint.

The success of the crystal-glass makers depended on their skill in purifying the alkali and on efficient grinding. Ten parts of crude alkali and one of calcined tartar were boiled in copper tanks, preferably lead-lined, like those used by the dyers (plate 31). After half the water was boiled away, the strong lye was left to settle for several days and the clear solution was decanted into earthen vessels. The more careful glass-makers carried this out three times. The solution was then returned to the cleaned boiler and evaporated until it started to 'spit', when the drying was completed in wooden containers. The 'salt' was then dried off completely in the furnace and broken up by grinding. During the seventeenth century the amounts of materials used increased considerably, and the pots were made to hold up to 2 cwt of melt. For this reason stone mortars for grinding gave place to the horse-mill, which consisted of a marble stone about 10 in thick and 7–8 ft in diameter turning on a hard marble floor. One horse turning such a mill could grind as much as 20 men using mortars.

Though there were many special and often secret mixtures, there were in fact relatively few basic colouring-materials. The colours were first ground and put through a fine sieve, and then fusion was carried out in a furnace distinct from that used for crystal. Further, a separate pot was kept for each colour and used only for that. Sea-green, the principal colour, was obtained by means of calcined brass and a fourth part of zaffre. A deeper green was produced by using *crocus martis* in place of zaffre. The principal blue was made by adding calcined sea-salt to the sea-green mixture, and a deep blue by zaffre alone. Darker shades were obtained with more colouring-matter and manganese ore (found near lead ores, such as those mined on Mendip, Somerset). Manganese was commonly known as 'pottern ore', being used by the Delft-ware makers to colour black, as zaffre was to produce blue pottery, glass, and artificial sapphires.

Though smalt and zaffre were so highly prized and widely used, they were obtainable only from Saxony, and their composition was for long unknown. The earliest accurate description appears to be that of Martin Lister, written for the Royal Society and found among Hooke's papers. Lister said that it was made from the ore called cobalt dug up at Schneeberg in Misnia, a province then under the Duke of Saxony. After heating the ore in a reverberatory furnace to drive off the arsenic, it was crushed in a stamp-mill and afterwards calcined, ground, and put through a sieve provided with a cover to hold down the dust. It was then mixed with fine quartz and allowed to harden in barrels. This *zoffloer*, as the miners called it, was broken up with sledge-hammers before sale or export. To make smalt the calcined cobalt was mixed with sand and potash and fused to give a dark glass, which was ground between very hard stones.

XI. SOAP-MAKING

Dyeing and glass-making were not the only trades consuming considerable amounts of potash and soda at this time; the soap-boilers probably used even more, and it is likely that the trade in imported ashes began in order to supply their needs. Kelp and home-made potash, together with lime, were also used. By 1500 the manufacture of soap had already been established for some centuries, a variety of fats and oils being boiled with a lye made from moistened alkali mixed with quicklime (figure 426). Tallow-soaps were more common in northern Europe, whereas olive-oil soaps were made in Spain, France, and Italy. Bristol, Coventry, and London had been early centres for the former, whereas the latter were made and exported particularly by Venice, Savona, Genoa, Castile, and later Marseilles. A black soap was made from the residues of lamp-oil at Amiens and Abbeville in Picardy. Tradition, however, was changing at the beginning of this period, for a London account of the trade in about 1500 shows that the soap of commerce, sold in 30-gallon barrels, was made from tallow and olive-oil from Seville, imported ashes, and unslaked lime. On the other hand, writers like Alexis of Piedmont [6] gave recipes for making soaps from suet and deer's grease heated with caustic alkali.

Soap-boilers were to be found wherever oils, fats, and alkalis were readily available: it was said that every citizen of Bristol was or had been a soap-boiler. The trade also extended to places where native soda could be had from the land merely for the taking. Thus in the seventeenth century it was reported that at Smyrna 10 000 quintals of oil were used annually for soap-making, 1500 camels being used for 8 months of the year to transport 'soap earth' (probably natron or trona, sodium sesquicarbonate) to the boiling-house. This earth was collected in the early morning from the plains near the river Hermus, some miles to the north. The lixivium was formed by mixing three parts of the 'earth' with one of lime and boiling.

In general the lye for soap was made in the way described by Tachenius [8]. Ashes were placed in barrels or troughs, moistened, covered with unslaked lime, and left for a time. They were then mixed together, water was poured over them, and the lixivium was run off as soon as it was strong enough to float an egg. A second, weaker lixivium was then obtained by adding more water. This second lye was boiled with the oil or fat until a curd formed, when the stronger lye was added, roughly in the proportion of three parts to one of oil, and boiling was continued until the curd became compact and apparently homogeneous. A crude test was then used to ascertain whether or not the proportions had been correct. If the product was sweet to the taste, more alkali was added, and if biting, more oil was poured in to use up the excess alkali. The curd was then set out on platforms or in boxes until it was dry enough to be packed into barrels.

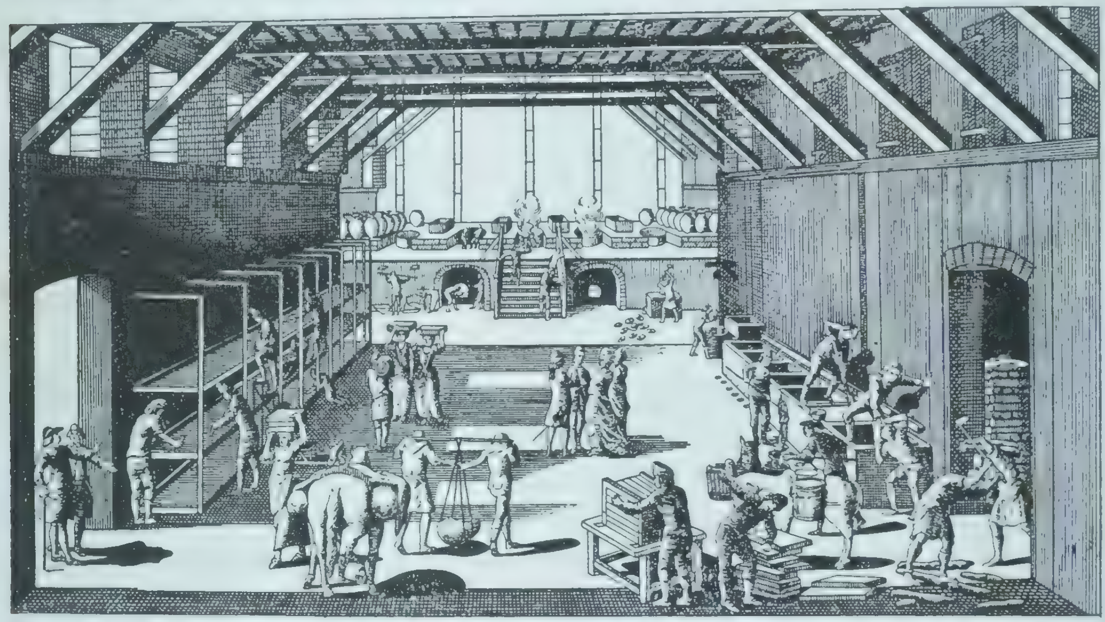

FIGURE 426—*General view of a soap-works. At the rear, the boilers with containers for oil and lye.* (Left) *Weighing and carrying out cakes of soap, and tables on which the hot soap cools and sets;* (right) *splitting wood, making and boiling the lye;* (centre) *packing soap.*

Though the preparation of the caustic lye was conducted with care, the strength of the alkali was not measured with any exactness, nor was there any attempt to determine the relative quantities of alkali and fat to be used in any one boiling. The need for better control of the process was, indeed, realized by the end of the period, but in general chemists were unable to make any considerable contribution until late in the eighteenth century. Thus no great advances could be expected. Nevertheless, other sources of oils were now becoming significant. Whale-oil was obtainable in quantity from the fleets working off Greenland, and fish-oil from other ships sailing to the fishing-grounds off Newfoundland. In earlier centuries supplies of these oils were limited, but when they became cheap enough the soap-boilers were not slow to make use of them; the products were, however, unsuitable for many purposes, such as cleaning wool, owing to their offensive odour. So close did the connexion between these trades become that in 1674 a co-partnership was formed in Glasgow for carrying on both the whale-fishing and the soap-boiling. It also seems to have been known that it was advantageous to add salt to the cauldron towards the end of the boiling-process, thus allowing the soap to separate out better and to become more compact. The true salting-out process, however, with quantitative control, was not introduced until towards the end of the eighteenth century.

Owing to the great variety of materials used, commercial soap varied from white to black, from hard lumps to soft paste, from Castile soap of good quality to the crude product from unpurified whale-oil. Clearly few of these products were suitable for domestic and personal uses without further treatment, but during this period there was a growing demand for domestic soaps, and many recipes were published to enable them to be made in the kitchens or still-rooms of great houses. They appear to have been introduced first at Naples and Venice, common hard olive-oil soap being grated, mixed with scented waters, and rolled into compact balls. Other domestic soaps were made from 2 parts of potash (that from poplar-wood was sometimes deemed best) and 1 part of quicklime, 8 potfuls of lye of the usual strength being employed to every potful of melted strained suet or kitchen grease. The mixture was heated almost to seething in a large-bottomed vessel lined with lead, and was then left in the sun for a week, being stirred at intervals until it formed a paste. Musk-rose water was added, and the mixture left in the sun for a further week, after which it was rolled into balls and kept lying in waste cotton or wool in a wooden box. Other varieties made from olive-oil were frequently perfumed with powder of violets and spices.

XII. CONCLUSION

The types of chemical industry discussed in this chapter have not included the manufacture of basal chemicals, such as acids, alkalis, and salts. At this time such materials were usually made by those who required them as the need arose, or obtained in relatively small quantities from 'chymists', namely, those skilled in chemical preparations. The large-scale production of these raw materials of modern industry belongs to a later period. There were some exceptions, notably alum, saltpetre, and copperas, which were purified by crystallization before sale, but the methods by which they were made had undergone little change throughout the centuries, and they do not afford very instructive examples of advances in chemical technology. Thus some of the fullest accounts of the preparation of acids and salts are to be found in treatises on metals, and that of alkalis in descriptions of soap-boiling and glass-making. Frequently such preparations were regarded as normal parts of manufacturing processes and they were sometimes tedious, particularly if pure substances were required. Improved methods for the distillation of strong acids for use by assayers were introduced, but success often required painstaking care. For example, *aqua fortis* was made by distilling a mixture of nitre or saltpetre and calcined vitriol, but the directions often include the manual separation of salt and similar impurities from the former to avoid producing an *aqua regia* (mixture of nitric and hydrochloric acids). The latter was, indeed, made by adding salt (sal ammoniac was apparently used in Italy) to *aqua fortis* and redistilling. The vitriol was also required to be as pure as possible, and the varieties obtained from Hungary and Goslar were especially recommended. Though alum could be used instead of the various vitriols, its high water-content made the calcination more costly and it was therefore avoided.

By 1730 the point had been reached where science, and particularly chemistry, could begin to give a lead in several manufactures. Before this time one may generalize by saying that trade practices were ahead of the science. Nevertheless, many were already looking to men of science to introduce novel methods and processes, and even the critics of science seem to have assumed that this should be so, though bemoaning the fact that results had not yet come up to expectations. Thus in 1724 Bernard Mandeville (1670?–1733), referring to the 'perfections' that had been reached in several trades, claimed that 'the many improvements, that can be remembered to have been made in them have for the generality been owing to persons who either were brought up to, or had long practised and been conversant in those trades, and not to the great Proficients in Chymistry or other Parts of Philosophy, whom one would naturally expect those things from' [13]. In the later volumes of this work there will be much greater evidence than could be produced here of the power of science to minister to the needs of industry.

NOTE ON THE PAINTINGS FROM THE PALAZZO VECCHIO, FLORENCE

THE paintings from the Palazzo Vecchio reproduced as plates 28–31 are some of the wall decorations in the study of Francesco I de' Medici, planned by Vasari and completed in the period 1570–2. This study is a recess entered by a door from the Great Hall, and two secret passages within lead from it to the treasure-room of Cosimo I, likewise built by Vasari in 1559–62. Francesco, it is said, loved alchemy and the mysteries of nature.

The pictures are held to represent the best work of the late Florentine School. There is a double series of paintings round the room, the lower frieze being movable and arranged so as to conceal cabinets and safes. The four paintings used here are from the upper frieze, and there is some reason to suppose that they were meant to portray the arts as then practised. Cavalori, for instance, who painted the wool-dyeing scene, was the son of a dyer living a short distance from Florence, near Sant' Ambrogio. The much-travelled Dutch artist, Jan van der Straat, painted the so-called alchemist, or maker of distilled waters, extracts, and chemical preparations. This was based on an earlier engraving (vol II, plate 42B).

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EPILOGUE

THE RISE OF THE WEST

A. R. HALL

I. CHANGING INDUSTRY

In the *Epilogue* to volume II (pp 756–71), attention was drawn to the technological superiority of the east over the west throughout the classical period, and during the greater part of the Middle Ages. The eastern, Greek portion of the Roman Empire certainly developed higher skills than did the western, Latin portion; and very possibly the civilization of remote China was more technically accomplished than that surrounding the Mediterranean basin, with which volume II was chiefly concerned. Such broad comparisons between two very different cultures cannot yet be made with absolute confidence, or in great detail; it is certain, however, that before the close of the Middle Ages the balance began to swing, and the technological superiority of western Europe to emerge. Many aspects of the movement, which was founded on the twin processes of transmission and invention, are discussed in the second volume and in various chapters of this one.

In the period treated in the present volume the dominance of the west was confirmed. It is true that political reflection of the economic and technological importance of Europe was delayed: the last Turkish siege of Vienna occurred as late as 1683, and by about the same date Europeans had established their rule overseas only in the East and West Indian islands, at a few points on the coast of India, and sparsely in North and South America. Mass emigration from Europe did not begin until after 1800. In the sixteenth and seventeenth centuries Europeans sailed their ships and carried their trade over the oceans of the world; they left home for South America or the Indies to make their fortunes; but they seldom intended to settle in distant lands, or to establish their industries there. Only in Central and North America was there a considerable population of European descent. Yet if the role of the European in Asia was still limited to that of the merchant, it was one from which he could not be displaced. Conscious of their unassailable position, merchants demanded commercial privileges, and disputes over them often led to wars. From military victories followed the necessity to assume administrative and political authority.

Thus, granted the immense European naval and military superiority, European control of the Far East was an almost inevitable consequence of Europe's commercial intrusion in the fifteenth century. Conquest, like missionary effort, was an aspect of the boundless energy of the west.

It was the western ascendancy in warlike affairs, ship-building, and navigation that first impinged upon the east. Western manufactures could tempt the primitives of Africa and the Americas, but they were as yet neither so excellent nor so cheap as to commend themselves highly to the civilized peoples of India and China. Indeed, eastern wares were acquired with bullion rather than by exchange of goods, and the craftsmanship of the east had greater influence on that of Europe than vice versa. Through their combination of artistic delicacy and technological refinement, certain products of the east—of the past rather than the present—are still unsurpassed. This brings out an important point in the history of technology, which is particularly relevant to the present period, namely that, in certain kinds of work, art and technique are inseparable. We cannot, in appraising a Chinese porcelain dish, divorce our admiration of the potter's sense of form, colour, and line from our wonder at his mastery of the wheel, of pigments and glazes, and of furnace control, without which artistic sense alone would be frustrated. Conversely the most developed engineering, chemical, and pyrometric skills cannot supply a want of artistry in design. While, therefore, it is obvious that many kinds of manufacture of high artistic merit would be unattainable without a certain minimum degree of technical proficiency—such as ancient goldsmith's work (vol I, ch 23, vol II, ch 13), or medieval ceramics (vol II, ch 8) and silks (ch 8)—it is also true that when advance to a yet more developed stage of technology occurs, it is likely to take place (as J. U. Nef has pointed out in chapter 3) in industries where quality is less important than quantity, beauty than serviceability.

There are several good reasons why this should be so. As in the fine arts, at the highest level of craftsmanship—working in gold or ivory or porcelain, for example—the personal contribution of the designer is so great that it is difficult to see how it can be replaced: moreover, the exceptional craftsman is likely to be more conservative in his methods than the ordinary artisan. Technological advances are usually directed towards the standardization and repetition of a good article in large numbers; but the rarity of works of exceptional craftsmanship is part of their virtue. For the same reason there is less significance—and less profit—in discovering an improvement to a manufacture whose products are bought only by a restricted group of wealthy patrons; inventors have always been attracted by large markets. Again, the basic mechanical or chemical processes involved in the making of goods for general consumption are likely to be simpler in nature than those used where the product is more perfect and expensive: hence it will tend to be easier to transform them. For example, it was easier to employ machines in working wrought iron than in working steel. Mass-production, or the substitution of a cheap material for a costly one, may bring about an actual deterioration of quality: thus coke-smelted iron was for long inferior to that smelted with charcoal.

Exceptions brought about by special circumstances naturally suggest themselves. Workers in precious metals first used protoscientific metallurgical techniques (ch 2). The silk industry devised the punched card, since so frequently adopted for 'instructing' machines (ch 7). In the manufacture of scientific instruments precision engineering begins on the small scale (ch 13). Rifling was applied first to sporting guns (ch 14). Where accuracy has been specially required, as by scientists, navigators, governments controlling currency, and so on, there has always been an incentive to devise improvements that might subsequently prove to have wide application, even though the initial market was small. Yet the huge, basic steps in technological progress seem to be linked with the satisfaction of the most elementary and insatiable human needs. Water- and wind-power were first applied to the grinding of corn, then to fulling cloth, then to mining and metallurgy. Steam-power went first to the mines, then to the mills. Mass-production methods appear first in ship-building yards, then in armament factories. Modern chemical industry begins with the 'heavy' chemicals, and so on. In some cases, moreover, where a new technique was initiated in a small way in a comparatively trivial industry—as when powerful presses were used to shape metal for coinage (ch 13)—it is clear that the real importance of the technique begins only with its application in a major industry.

Thus the generally higher level of technical proficiency in Europe in the seventeenth century compared with the rest of the globe is in no way inconsistent with an inferiority in the quality of certain articles, such as silks or ceramics. The superiority of the west lay in its greater use of power and machinery, in its chemical industry, and, in a few respects, in its applications of natural science. These advantages enabled Europe to produce more goods more cheaply, and so gradually to raise its standard of living to an unprecedented level, while dominating the commerce of the world and drawing to itself every necessary raw material.

As might be expected, the rate of technological change varied in different countries and followed somewhat different paths. In the early sixteenth century many crafts were more advanced in southern Europe, especially in Italy, than in the north. Italian metal-workers, potters, and silk-weavers were unrivalled;

many of the machine-books and other technological treatises were the work of Italian writers, who had the skill of the finest printers at their command; and in Italy, too, at this period, science had its most lively progress. The tendency here was towards higher craftsmanship—Cellini (p 338) is perhaps its supreme example—rather than towards radical transformation of the methods of production, and the trades supplying wealthy consumers were those most affected. France followed somewhat the same path later: it is well known how Colbert (1619–83; p 464) encouraged her luxury industries, such as silk-weaving and the manufacture of tapestries at the Gobelins establishment. Gradually, however, the emphasis shifted to northern Europe, where it remains throughout the following volumes of this *History*. Northern France, the Low Countries, northern Germany, Sweden, and Britain become increasingly influential as centres of industry and commerce. The products of this northern industry were often inferior in quality—as may be seen in printing, ceramics, textiles, and glassware, for example—but the scale of operation was larger.

The rise of the north is best exemplified by Britain. In the Middle Ages the position of the British Isles on the northern fringe of Europe, that proved so valuable to their commerce later, had rendered them isolated, uncultured, and of relatively small import in international affairs. Only political and administrative institutions were well developed in England—these, too, contributed to her industrial success; the remaining kingdoms were semi-barbaric. Even in 1500 Britain played but a lowly part in international commerce as the source of wool and unfinished cloth, tin, hides, and a few other materials. Most of her distant trade was in the hands of Venetian and Hanse merchants. By 1700, however, British ships sailed freely on the world's trade-routes, and numerous export industries flourished, especially that of dyed and finished cloth. Britain's need of many commodities, wholly imported in 1500, was now supplied by new manufactures, which were well able to compete with oversea producers. This growth of an industrial economy in Britain was partly effected by direct imitation of foreign methods and with the aid of foreign workmen, but in its later stages especially it owed much to native technical resourcefulness, of which many instances have been quoted in this volume, particularly the use of coal fuel (ch 3).

Now British industry did not thrive because its workers were more skilful than those of other countries: rather, the reverse was true. Even British shipbuilding, the nation's pride, was in many respects inferior in design and practice to that of the French and Dutch. Britain's industrial success, incipient in the eighteenth century and fully assured in the nineteenth, is essentially to be attributed rather to her richness in the two great materials of the age, coal and iron, and to the readiness with which her manufacturers exploited them. To say this is, of course, to simplify a complex process, for the success must be attributed to many social, economic, and political factors, but for the present purpose the technological adaptability of British industry is the outstanding fact (pp 76–80). British manufacturers were constantly active in replacing skilled workers by machinery, in finding substitutes for scarce and costly materials, in hastening or cheapening processes. They steadily resisted attempts to fossilize their business in the supposed interests of their workpeople or of the quality of the product. Those of other nations were moving in the same direction, but less swiftly and less successfully in most branches of industry, and especially in the heavier trades.

The movement was towards a new kind of industry, whose social implications were tremendous. Before the eighteenth century, and later still outside the confines of Europe, productive techniques were of two kinds. Relatively crude methods were used by village artisans and household workers to make the coarse, sturdy articles of common use; more refined and tedious methods were employed by artists, of a different class altogether, to furnish the rich merchants and the landed gentry with their more delicate commodities. Compare, for example, peasant pottery with the products of the kilns of Deruta and Caffagiolo; the harsh stuff of soldiers' uniforms with the dress of a well born officer; the low, earth-floored dwellings of the labourer with the solid masonry and elegant plaster-work of the town house. The difference is not merely that yielded by the contrast between poverty and riches: it is a distinction of technological accomplishment. No social displacement could overcome it. The skilful methods of the exclusive craftsman might be destroyed, but they could never be extended to the supply of the multitude. To overcome it a technological change was required, one that would ultimately destroy the livelihood of most ordinary artisans and domestic workers, though it will probably never wholly destroy that of the exclusive craftsmen—tailor, chef, bookbinder, and the like—whose service to their patrons is almost of a personal nature.

Medieval manufacture was either widespread, crude, and economically inefficient or exclusive, highly dextrous, and likewise economically inefficient. The new technology of the eighteenth century was to be efficient, technically advanced, and yet wide in its markets. It sought to supply from the same establishments and by the same methods not only the more exacting requirements of the wealthy and cultivated classes of society but the needs of those who were less fortunate. Consequently there tended to prevail a condition approximating more and more closely to a state of technological homogeneity—the difference between the methods used to produce cheap goods and those used to produce costly ones tended to disappear, though the latter were made from better materials and more elaborately finished or decorated. In our own time the obliteration of visible social and economic distinctions in dress is a commonplace, but even within the period of the present volume articles made of fine earthenware, metal, and glass entered into more common household use everywhere, whereas formerly the poorer classes had used articles made of wood and horn; this was a result of technological developments already described.

As everyone knows, the disappearance of the village artisan, of the household worker, and of the exclusive craftsman was brought about by the growth of the factory system, and this in turn was promoted by the adoption of new techniques of manufacture. This growth was scarcely evident before the eighteenth century in Britain, and occurred even later in America and continental Europe. It will be discussed further in subsequent volumes of this *History*, but it should be noted here that factors permitting this development of manufacture in large establishments, making extensive use of machinery and power, were forming much earlier. One reason for the occurrence of this development in Europe, rather than elsewhere in the world, would seem to be the operation of these factors in the European economy in a manner that cannot be discerned elsewhere. Something of this development is mentioned below. In connexion with the growth of large-scale industry and the implementation of new processes, however, it is convenient to discuss two of the factors here: the accumulation of capital (without which investment in machinery and plant would be impossible) and the evolution of suitable means for putting capital into service.

There have always been rich men, and partnerships and complex financial arrangements between merchants were not confined to the economic life of Europe. Yet there can be little doubt that the financial systems that had grown up in Europe by the end of the seventeenth century were more serviceable than those known elsewhere. Already in the Middle Ages the currencies of the various states had become fairly stabilized, a rudimentary kind of private banking flourished, and a convenient method of conveying credit from one merchant to another without any actual shipment of money was working. Already, too, there was considerable evidence of a willingness to invest in industry as well as trade —for example, in the construction of water-driven machines for the textile industry of Britain or the metallurgical industry of Germany. By the sixteenth century great banking families like the Fuggers and the Welsers were financing emperors, there was an organized international money-market at Antwerp, and in many parts of Europe the great landed proprietors, following the example of the merchants, were investing in industrial development on their estates.

Oceanic trade prompted still another form of mercantile arrangement, that of the joint-stock company in which many combined to finance an enterprise beyond the resources of an individual. By the end of the seventeenth century an embryonic share-market of the modern type existed—though it was far more concerned with trade than with manufacture—and public banks, such as the Bank of England (1694), had been founded. Thus the old conception of wealth as gold safely locked in a stout chest or as broad acres of rich land was weakening, though not entirely destroyed, and men were accustomed to investing their money at risk in the hope of large ultimate profits. In the years of the notorious South Sea Bubble (*c* 1720) gullible investors were tempted to venture their capital in a host of projected new manufacturing enterprises. That they did so is a measure of a changed attitude, which made possible the private encouragement of the more fortunate pioneers of the industrial revolution and, later, public investment in canal and railway systems. Without the means for raising capital that already existed in 1700 this could have happened only very much more slowly, if at all.

II. TECHNOLOGY IN EUROPEAN HISTORY

In the period of this volume, therefore, the curve of technological history bends sharply upwards, and at its close we are on the threshold of the age of steam and iron. The techniques of the rest of the world (apart from European-settled America), remaining for a long time unaffected by this rapid and conspicuous development as they had formerly been untouched by the less obvious changes that had prepared the way for it, stagnated at the craftsmanship level and indeed yielded works of inferior merit to those of former times. This *History* follows the curve in pursuing the course of events in Europe. The causes lying behind these events, behind the development of power and machinery, are obscure, and it would be inappropriate to discuss them at length here. As with most complex historical processes, causes and effects seem to be inextricably interlocked, each playing upon the other. Expanding markets stimulated technological improvements to facilitate larger production; large production inspired a search for yet wider markets; each step forward in technique encouraged other attempts at invention; and so on.

Medieval Europe began with many advantages. It derived a rich scientific and technical heritage from the ancient world, yet it was not paralysed in initiative by veneration of past glories. Its natural resources in water, wood, coal, metals, salts, and other minerals were large and accessible; its agricultural potentialities were great and its climate varied. The peoples of the west were basically united in religion, had a common language of learning, and enjoyed a relatively easy communication with each other. After the tenth century A.D., though there was much internecine warfare, there was no great barbarian invasion into the heart of Europe. Its population was small enough to offer to all in normal times ample land and opportunity to work; as the population steadily grew the possibility of economic expansion grew with it. Slavery died out, and, though the gross exploitation of human labour did not thereby cease, the value of labour was always recognized. For many centuries Europe has been conscious that the reduction of the labour element in the production of an article usually leads to a reduction in price.

The social system of medieval Europe was in other ways also more liberal than that of any ancient state, or of any oriental civilization. Feudalism was a powerful and conservative force in society, but with growing confidence from the twelfth century onwards riches, comfort, and even political influence could be won through success in trade and manufacture. Long before the end of the Middle Ages some communities—the north Italian states, the Hanse towns, the Rhineland Free Cities, the City of London—were controlled by their merchant class. This class, and the broad development of trade and industry, were encouraged by secular rulers for fiscal and other reasons of prudent policy. Moreover, the society of medieval and of early modern times was tolerably stable: despite wars and minor disturbances it was not shaken profoundly by dynastic upheavals or by widespread revolution. Its rulers were not, generally, tyrannical; they did not seek to force men's lives into a set pattern, or to fossilize their states by an excess of bureaucratic control such as was evident in the last centuries of Rome and the later periods of Chinese history. European society between, say, the twelfth and the seventeenth centuries was far from absolutely free—no society can be without its restraints—but it was probably more free than any before.

These were conditions making for prosperity and expansive development. Many rewards were offered to the ingenious and industrious individual, however humble his origin, and academic learning was relatively freely available to those who could profit from it. In this connexion it is worth emphasizing that although printing is far older in China than in Europe, it was in Europe that full technical advantage was taken of the invention of movable type. The development of literacy in Europe, and from this, that of the book and periodical as vehicles of scientific and technical instruction, are unparalleled elsewhere. Perhaps European civilization could not have progressed so rapidly had it not possessed a remarkable faculty for assimilation—from Islam, from China, and from India. No other civilization seems to have been so widespread in its roots, so eclectic in its borrowings, so ready to embrace the exotic. Most have tended (like the Chinese) to be strongly xenophobic, and to have resisted confession of inferiority in any aspect, technological or otherwise. Europe would yield nothing of the pre-eminence of its religion and but little of its philosophy, but in processes of manufacture and in natural science it readily adopted whatever seemed useful and expedient. From the collapse of the Roman empire onwards there is indeed a continuous history of technological change in Europe, slight at first, but gradually becoming more swift and profound. It would therefore be idle to discuss how this began, for it has always existed.

III. INDUSTRY AND SCIENCE

In the last two and a half centuries, and above all in the last hundred years, a new factor has contributed to the headlong evolution of European technology: natural science. As already indicated in the preface to this volume, science only rarely played such a part earlier. Some of the technical changes of the Middle Ages that might have been attributable to the scientific developments of the thirteenth century—the introduction of gunpowder, for instance, and of the seaman's compass—prove rather to be products of assimilation from outside Europe. The rudimentary scientific knowledge associated with the application of these technical innovations, as in navigation (ch 19 and 20) and the art of war (vol II, ch 20; ch 14), was itself imitative in origin. Medieval science was grounded firmly on ancient classical authors, whose work became known in the Latin-writing west mainly through translations made from Islamic sources. Then, from the fourteenth to the sixteenth century, and especially between *c* 1450 and *c* 1550, European activity in science was again invigorated by renewed attention to its classical origins, now by way of direct translation from the Greek and by the study of authors previously unknown or neglected. Little of the science usually taught about the year 1500 would have been incomprehensible, or perhaps unfamiliar, to a well educated man of the second century A.D. The great age of creative rather than assimilative science in Europe, that in which fundamental conceptual and practical discoveries took knowledge far from its classical foundations, did not begin until about the middle of the sixteenth century. Thenceforward progress was indeed rapid: within another century the pursuit of scientific truth in ancient authors had been quite abandoned. By about 1650, for example, the basic facts of topographical anatomy were securely established, while by 1700 the elements of mechanics were practically complete—and mechanical science could take both heaven and earth within its view. Scientific academies had been founded, and new ideas and methods were making their way even in the traditionalist universities. Everywhere new techniques of mathematics, and new scientific instruments whose number increased yearly, permitted an ever wider and deeper view into natural phenomena. At this time, too, with the first Jesuit missions in China, European science began to displace its equivalent in the older Asian civilizations.

It has been pointed out already in this *History* that the non-speculative bases of science—all derived from experiment, observation, or experience—owed far more to technology and craft-knowledge than technology owed to science. This was largely true at least as late as 1700, and the exponents of the 'new philosophy' of experimental science had been conscious of the fact. As Robert Boyle wrote, about 1659:

> 'Tis a prejudice no less pernicious than general which natural history and the interest of mankind receive, that learned and ingenious persons should have been kept strangers to the shops and practices of tradesmen [artisans]. . . . Most of the phenomena that arise in trade [industry] are a part of natural history [science]: and therefore demand the naturalist's care . . . they show us nature in motion, and that too when turned out of her course by human power, which is the most instructive state wherein we can behold her.

Boyle, developing an argument of Francis Bacon, is, indeed, arguing that the scientist has not learnt as much from technological experience and practice as he should. Many efforts were made to give effect to this view—for example, by the Royal Society in its early years—and though the direct results were not very illuminating, such efforts did strengthen the attempt to render science more realistic and practical. Most of the great scientific figures of the seventeenth century, from Galileo to Newton, were deeply interested in the double link between science and technology, and in establishing a hopeful cross-fertilization between the two. In this *History* it has been possible to profit from the same interest among the members of the French Académie des Sciences, for many illustrations reproduced here were originally drawn for the comprehensive account of all trades which the Académie projected.

It was argued with equal cogency that, despite its immediate dependence on technology for useful information, the advance of science must in the long run inevitably hasten technological progress towards that 'Empire of Man over Nature' which was contemplated by Bacon. This delightful vision of an existence in which work would be eased by wonderful machines, thought speeded round the world, and life given unimaginable colour and softness by new chemical processes, while men admired the marvellous intricacy and providence of the Creator's work, was portrayed in a score of treatises, many of which have been referred to earlier in this volume. Bacon's 'New Atlantis' (1627) is the most famous attempt to describe a society in this state of scientific-technological bliss, of which, however, its author recognized that the increased power of destructive weapons must be a part:

> We have divers mechanical arts [in the Salomon's House] that you [Europeans] have not, and stuffs made by them, as papers, linen, silks, tissues, dainty works of feathers of wonderful lustre, excellent dyes, and many others; we have also furnaces of great diversities, but above all we have heats in imitation of the sun's and heavenly bodies' heats. We have also perspective-houses where we make demonstrations of all lights and radiations; we find also divers means, unknown to you, of producing of light originally from several bodies. We have also engine-houses, where are prepared engines and instruments for all sorts of motions. There we imitate and practise to make swifter motions than any you have, either out of your muskets or any other device. We also represent ordnance and instruments of war, and engines of all kinds; and likewise new mixtures and compositions of gunpowder. We imitate also flight of birds; we have ships and boats for going under water. We have divers curious clocks, and some perpetual motions.

Men had long before dreamed of acquiring such control over their natural environment by magical means, but by the seventeenth century magic had been abandoned. The scientific power over nature was to be of the same kind as the imperfect one men already exercised, one obtained through reason, experiment, and observation. Such a power had been hinted at before. In a famous passage Roger Bacon accurately anticipated many later achievements, *c* 1250:

> Machines for navigation can be made without rowers so that the largest ships will be moved by a single man in charge . . . cars can be made so that without animals they will move with unbelievable rapidity . . . flying-machines can be constructed so that a man sits in the midst of the machine revolving some engine by which artificial wings are made to beat the air like a flying bird . . . machines can be made for walking in the sea and rivers, even to the bottom without danger.

Too much importance should not be attached to such a prophecy. Many men in many periods have dreamed of attaining the seemingly impossible; what is significant, from the latter part of the sixteenth century onwards, is the faith that the seemingly impossible will ultimately surrender to the patient, systematic assault of natural science. By about 1700 this faith was already partially justified by works. Ships were navigated by science; steam was harnessed; the possibility was even open that the most unpredictable of all factors, the weather, might be susceptible of prediction. In the chemical industries especially the preparation of many substances was now notably more scientific than it had been a century before, and practical chemists like Boyle, Glauber, Kunckel, and Lémery were eminently more rational in their outlook than their predecessors. At last, in the ill-fated theory of phlogiston, a temporarily successful attempt was made to explain the phenomena of chemical reactions and combinations in terms consistent with practical experience.

Roger Bacon's words serve also as a reminder of the truth, often demonstrated in this *History*, that in the Middle Ages the ambition to make technical or industrial progress was by no means wholly latent. In the sixteenth and seventeenth centuries such ambition found many opportunities. Geographical discoveries burst open the horizon; American silver wrought an expansive inflation, swamping economic barriers and restraints; a new world of thought and learning was discovered. The idea that men control their own destinies, both here and hereafter, seized their minds. Projects and inventions multiplied: the vast growth of technological literature, much of it filled with suggestive new ideas, has often been mentioned. Most of this flood of invention was devoid of any basis in science or experience, much was wild and ended in disappointment. Even many well planned attempts—for the rapid consolidation of an agricultural science, for example—necessarily failed. Yet some inventors, choosing a propitious subject and persisting in their labours, succeeded, and a pattern of success was established. Still more successful in its parallel course was science itself, and it was perhaps hard to believe that men who could see the hidden corpuscles of the blood, or calculate the forces holding the planets in their courses, could not solve also the more mundane problems of setting steam to work, or making steel cut like diamond. Everyone knew that navigation had called astronomy to its aid, that chemistry promised to subjugate disease: why should not all material problems of civilization yield to the same method, placing in European hands a power and enlightenment such as the world had never seen? Already by 1700 many were proclaiming that the 'moderns' of Europe had at last hit upon the track to boundless knowledge and prosperity missed not only by the Greeks and their predecessors but by the other civilizations with which they were already familiar. Those who sounded this note placed their emphasis on the triumph of science.

It is hardly surprising, then, that starting from such solid achievements, with such ambitions and such confidence, Europe began in the eighteenth century on that tremendously accelerating acquisition of technical mastery which will be traced in the next two volumes. In our own age, when European society seems to be contracting on itself, when its influence in the world declines and Asia eagerly seizes the mechanics of European civilization while repelling its spirit, it is difficult not to be impressed by the thriving, ebullient expansiveness of the Europe of the seventeenth century. It was a brilliant age, yet it looked to greater glories in the future. Within five or six centuries this society of Christian people had risen from fear and barbarism not merely to great achievement in the arts and to domination of the globe but to a position in which it could face Nature, and almost, it would seem, its Creator, on terms of intimacy and understanding. All that was best in the past and present experience of humanity Europe seemed to have drawn to itself and comprehended in itself: and the success of this creative assimilation gave a great impetus to progress. Men looked to the future now, not to the past, and perhaps for the first time in history had some inkling of the road to be traversed in time to come. They saw science as the inspiration of technology, and technology as the key to a life of richness and prosperity: what they could not see, however, was the infinite and tortuous complexity of man himself.

I. INDEX OF PERSONAL NAMES

The dates given for rulers are regnal dates, not years of birth and death

Abulcacim Abnacahm (*c* 1025), author of text on the equatorium, 616 *and* n.
Accum, Friedrich (1769–1838), chemist, author of 'Adulteration of Food and Culinary Poisons', 22.
Adād al-Daula, Caliph, *and* silver globe referred to in 1043, 612.
Adams, George (d 1773), scientific instrument-maker, 556, 645–6.
Adams, Robert (1540–95), surveyor of works to Queen Elizabeth I, *and* ships, 481.
Agas, Ralfe (*fl* late sixteenth century), surveyor, 317.
Agricola, Georgius (Georg Bauer) (1494–1555), physician and metallurgist, author of *De re metallica*, 27–30, 41, 50–2, 59, 62–3, 65, 82, 206, 208–10, 212–14, 216–17, 224, 324–33, 677, 691, 700.
Agrippa, Cornelius, of Nettesheim (1486–1535), German physician, *and* alchemy, 676–7.
Agrippa, Marcus Vipsanius (63–12 B.C.), Roman general, *and* survey of Roman Empire, 504.
Al-Battānī (*c* 858–929), *and* astronomical instruments, 590.
Alberti, L. B. (1404–72), author of *De re aedificatoria*, 250, 429, 446–7.
Alexander the Great (336–323 B.C.), Macedonian king, *and* town-planning, 275; *and* influence of conquests, 505.
Alexander VI (1493–1503), Pope, *and* town-planning, 288.
Alexander VII (1655–67), Pope, *and* town-planning, 289.
Alexis (Alessio Piemontese) (*c* 1555), metallurgist, 43, 679, 703.
Al-Farghānī (Alfraganus) (*fl* 861), *and* measurement of Earth's circumference, 522.
Al-Fazārī (*c* 800), writer on astrolabe, 609.
Alfonso X, The Wise (1252–84), king of Castile, *and* navigation, 526; *and* mechanical timekeepers, 648–9.
Alfred the Great (871–99), English king, *and* naming of winds, 518.
Al-Ḥākim (*c* 966), founder of observatory at Cairo, 584.
Alhazen, *see* Ibn al-Haitham.
Al-Kāshī (d 1436), Persian astronomer, 617.
Al-Khwārizmī (*c* 840), *and* portable quadrant, 608.
Allen, Elias (*fl* 1606–54), mathematical instrument-maker, 630–1.
Allen *or* Alleyn, John (? 1660–1741), Somerset physician, *and* fuel economy, 687.
Allgood, Edward (*c* 1730), *and* tinplate, 689.
— Thomas (*c* late seventeenth and early eighteenth century), *and* black varnishes, 688.
Allgoods, the (eighteenth century), *and* lacquering, 697.
Al-Ma'mūn (813–33) caliph, *and* libraries and observatories, 521, 584.
Aloysius Lilius (sixteenth century), Neapolitan physician, *and* Gregorian calendar, 579.
Alpini, Prospero (1553–1617) of Padua, describer of coffee plant, 5.
Al-'Urdī (thirteenth century), astronomical instrument-maker, 584.
Al-Zarqālī (*c* 1029–87), founder of observatory at Toledo, 584–5; and writer on the equatorium, 616.
Amant (*c* 1745), French clock-maker, inventor of pin-wheel escapement, 672, 674.
Ambrose, St, archbishop of Milan (? 340–9), dalmatic of, 202.
Amenhotep III (*c* 1415–*c* 1380 B.C.), Egyptian king, *and* water-clock, 601.
Amman, Jost (1539–91), wood-engraver, 43, 116, 122, 223, 388, 391–2, 394, 399.
Ammannati, Bartolomeo (1511–92), bridge designer, 430.
Andreolis of Gubbio (*c* 1500–40), *and* new colours for ceramics, 678.
Andreossy, François (1633–88), canal-engineer, 464–6.
Angelus, Jacobus (*c* 1409), translator of Ptolemy's *Geographike Syntaxis*, 530.
Anglicus, Robertus (thirteenth century), author of *Astrolabii Canones*, 537.
Archimedes of Syracuse (*c* 287–212 B.C.), mathematician, 22, 58, 66, 313.
Aristarchus of Samos (third century B.C.), *and* trigonometry, 503.
Aristophanes (*c* 450–385 B.C.), Greek dramatist, *and* calendar, 569.
Aristotle (384–322 B.C.), Greek philosopher, 272, 374; *and* form of the Earth, 504.
Arphe, Juan (*c* 1572), assayer, 64–5.
Arsenius, Walter (sixteenth century), instrument-maker, 540, 586, 621.
Ascham, Roger (1515–68), author of *Toxophilus*, 351.

Atwood, George (1746–1807), *and* scientific apparatus, 645.
Augustine, St, of Hippo (354–430), *and* existence of antipodes, 519.
Augustus (63 B.C.–A.D. 14), Roman emperor, 507; *and* survey of Roman Empire, 504; *and* Roman calendar, 577–8.

Bachelier, Nicolas (1485–1572), canal-engineer, 459, 464.
Bacon, Francis (1561–1626), *and* impact of science on the arts, 679–80, 717–18.
Bacon, Roger (*c* 1214–94), *and* lenses, 230; *and* maps, 521–2; *and* magnetic compass, 524, *and* scientific progress, 718–19.
Badeslade, T. (*c* 1724), cartographer, 316.
Badius Ascensius, Jodocus (? 1462–1535), printer, 397–9.
Baker, Matthew (1530–1613), master shipwright under Elizabeth I, 479, 487–8.
Bakewell, Robert (1725–95), stock-breeder, 15.
Baldewin, Eberhardt (*c* 1561), clockmaker, 658–60.
Barattieri, Giovanni Battista (*fl* second half of seventeenth century), hydraulic engineer and author of *Architettura d'acque*, 315.
Barba, Alvaro Alonzo (*c* 1620), metallurgist, 28–9, 63.
Barisino, Tommaso, of Modena (*c* 1352), portrait painter, 230.
Barlow, Edward (*c* 1676), clockmaker, 668–70.
Barman, Christian, 114.
Bartholomew the Englishman (*c* 1250), author of *De proprietatibus rerum*, 676.
Bartolotti (*c* 1630), hydraulic engineer, 314.
'Basil Valentine' (Johann Thölde) (*c* 1604), author of 'Triumphal Chariot of Antimony', 29.
Bauer, Georg, *see* Agricola.
Baumé, Antoine (1728–1804), scientist, *and* hydrometer, 22.
Becher, Johann Joachim (1635–82), chemist, 682.
Bede, the Venerable (673–735), *and* Christian chronology, 578; *and* shadow-length tables, 595–6.
Bedford, Francis Russell, fourth Earl of (1593–1641), 'undertaker' for drainage of the Great Level, 319.
— Duke of (1765–1805), stock-breeder, 15.
Behaim, Martin (? 1430–1506), *and* Jacob's staff, 591; *and* terrestrial globe, 614.
Belidor, Bernard Forest de (1693–1761), author of *Architecture hydraulique*, 324, 333–4, 344, 422, 425, 440–1.
Belknap, tool-making firm of U.S.A., 117.
Bernard, St (1091–1153), abbot of Clairvaux, vestment of, 198.
Bernini, Lorenzo (1598–1680), architect, 289.
Besson, Jacques (*c* 1573), author of *Theatre des instrumens mathematiques et mechaniques*, 328, 334–5, 337.
Beukelszoon, William (fourteenth century), Flemish fish dealer, 22.
Bezinghen, Abot de (*c* 1764), writer on coining-presses, 340.
Biondo, Flavio (1388–1463), author of *Roma Instaurata*, 288.
Biringuccio, Vanoccio (1480–1539), metallurgist, author of *Pirotechnia*, 27–8, 30, 34, 36–44, 47–50, 52–5, 59, 62, 65, 210, 212, 214, 364–5, 367, 368 n, 391–2.
Blache (*c* 1687), French mechanician, 165.
Black, Joseph (1728–99), chemist, 25.
Blaeuw, P. and J., Amsterdam (eighteenth century), printing firm, 402.
— Willem Janszoon (1571–1638), cartographer and printer, 400.
Blancourt, H. de (*c* 1697), author of *Art de la verrerie*, 678, 683, 698.
Blith, Walter (*fl* second half of seventeenth century), author of 'The English Improver Improved' (1652), 134–6, 321–2.
Blon, J. C. Le (*c* 1730), experimenter in mezzotint process, 408.
Blondeau, Peter (*c* 1649), coin-maker, 341.
Blondel, François (1616–86), mathematician and architect, 256.
Böckler, C. A. (*c* 1662), mechanician, 16–17.
Boëthius (480–524), Roman philosopher, *and* mathematics, 502.
Bogaerden, Adrien van (*fl* 1550–63), canal-engineer, 452.
Boizard, Jean (*c* 1696), assayer, 47–8, 59, 65.
Boller (*c* 1502), mechanician, 18.
Bologna, Fioravante da (*c* 1438), canal-engineer, 445.
Bonde, Carl (*fl* 1629–39), canal-engineer, 455.
Bontekoe, Cornelius (d 1685), Dutch physician, advocate of tea-drinking, 5.
Bouchon, Basile (*c* 1725), French mechanician, 166.
Boulton, Matthew (1728–1809), manufacturer, 368.
Bourn, Daniel (*c* 1748), inventor of rotary carding-machine, 154–5.
Boutheroue, François (*c* 1638), canal-engineer, 463.
— Guillaume (*c* 1638), canal-engineer, 463.
— Hector (*c* 1664), canal-engineer, 465.
Boyle, Robert (1627–91), chemist, 22, 37, 55–7, 68, 637, 681–3, 696–7, 717, 719.
Bradley, Humphrey (*fl c* 1584–1625), hydraulic engineer, author of a treatise on the draining of the Fens, 316–20, 459, 462.

Bradley, James (1693–1762), Astronomer Royal, 554.

Brahe, Tycho (1546–1601), Danish astronomer, 400, 582, 588–9, 621, 625, 640, 658–9.

Bramante (Donato d'Agnolo, 1444–1514), architect, 288, 338.

Bramer, Benjamin (1588–1650), mathematical instrument-maker, 626–7.

Branca, G. (1571–1640), mechanician, 342.

Brandenburg, Margrave of (*c* 1248), *and* town-planning, 285.

Brederode, Hendrik Van (sixteenth century), *and* land reclamation, 302.

Bredon, Simon (d 1372), *and* the equatorium, 617.

Bregandyne, Robert, 'Clerk of the King's Ships', *temp.* Henry VIII, 487.

Briot, Nicholas (*fl* early seventeenth century), coin engraver, 341.

Browne, Henry (*c* 1721), inventor of hemp-stamping machine, 159.

Brunelleschi, Philippo (1377–1444), architect, 245–6, 248.

Buckingham, Duke of (1628–87), *and* Italian glass-workers, 238.

Bullet, Pierre (1639–1716), architect, 293.

Buontalenti, Bernardo Timante (d 1608), hydraulic engineer, 309.

Bureus, Andreas (*c* 1628), canal-engineer, 455.

Burghley, Lord (William Cecil) (1520–98), Secretary of State, *and* draining of the Fens, 317–18.

Burgi, Jobst (1552–1632), Swiss instrument-maker, *and* clocks, 658, 660–2.

Butler, Pierce, author of 'The Origin of Printing in Europe', 385.

Buyten, Martin van (*c* 1586), engraver, 409.

Caesar, Caius Julius (102–44 B.C.), Roman dictator, *and* survey of Roman Empire, 504; *and* reform of Roman calendar, 576–7.

Calabrais, Jean le (fifteenth century), mechanician, 190.

Callippus (*c* 330 B.C.), astronomer, *and* Greek calendar, 571.

Campano da Novara *or* John Campanus of Novara (*c* 1261–92), astronomer, 522, 616.

Camus, Charles Étienne Louis (1699–1768), mathematician, 345.

Cantelupe, Walter de (1236–66), bishop of Worcester, vestments of, 201.

Caradosso (*fl* early sixteenth century), die engraver, 338.

Cardalucius, J. H. (*c* 1672), metallurgist, 41.

Cardan, Jerome (1501–76), philosopher, 17, 30, 658.

Carlberg, C. W. (*c* 1777–8), artist, 222.

Cartier (*c* 1771), French scientist, *and* hydrometer, 22.

Casal, Gaspar (1691–1759), Spanish physician, *and* maize as a cause of pellagra, 4.

Cassini, Jean Dominique (1625–1712), astronomer and cartographer, 544, 553–4.

Cassini de Thury, César François (1714–84), cartographer, 554.

Cassius, Andreas (? 1640–? 1673), glass-maker, 225.

Castelli, Benedetto (1577–1643), hydraulic engineer, author of book 'On the measurement of running water', 313–15.

Caswell, John (1656–1712), mathematician, 58, 544.

Catchpole (*c* 1860), Suffolk millwright, 101.

Catherine de Medicis (1547–1589), French queen, *and* snuff, 10.

Caus, S. de (1576–? 1626), engineer, on rolling-mill, 45, 342.

Cavalier, Jean (*c* 1664), Geographer Royal in France, *and* canals, 465.

Cellini, Benvenuto (1500–71), goldsmith, 48–9, 53–4, 338–9, 341, 358, 711.

Censorinus (third century), *and* Egyptian calendar, 564; *and* Roman calendar, 575, 578.

Chambéry, Perret de (sixteenth century), writer on town-planning, 290.

Charlemagne (768–814), emperor, king of the Franks, silk from shrine of, 196.

Charlemagne (*c* 1793), mechanician, 18.

Charles the Bold (1433–77), Duke of Burgundy, *and* destruction of Liége, 74.

Charles I (1625–49), English king, knitted vest of, 186; *and* land drainage, 320; *and* ships, 486, 494.

Charles II (1660–85), English king, *and* rebuilding of London after Great Fire, 297; *and* ships, 494, 497.

Charles IV (1346–78), emperor, velvet found in tomb of, 205.

Charles V (1519–56), emperor, *and* invention of small roller-mill, 16; *and* destruction of Vitry-en-Perthois, 290; *and* canals, 449.

Charles VII (1422–61), French king, *and* printing, 384.

Charles VIII (1483–98), French king, *and* invasion of Italy, 349.

Charles XI (1660–97), Swedish king, *and* technological laboratory, 682.

Chaucer, Geoffrey (? 1340–1400), poet, *and* 'chilindre' or shepherd's dial, 596; *and* 'Treatise on the Astrolabe', 609; *and* 'The Equatorie of the Planetis', 617.

Chaulnes, Duc de (1714–69), *and* dividing mechanism, 641.

Chézy, Antoine de (1718–98), author of *Mémoire sur la vitesse de l'eau conduite dans une rigole*, 464.

Ch'iao Wei-Yo (*c* 984), Chinese canal-engineer, 439.

Chiese, Philippe de (*c* 1662), canal-engineer, 454.
Chodowiecki, D. (1726–1801), engraver, 156.
Cicero, Marcus Tullius (106–43 B.C.), *and* reckoning apparatus, 501–2; *and* maps, 504; *and* Roman chronology, 578.
Clarke, Roger (*c* 1746), scientist, *and* 'Hydrometer or Brandy Prover', 22.
Claudius Clavus (Claudius Clausson Swart) (1388–14—?), cartographer, 532–3.
Clement IV (1265–8), Pope, *and* Roger Bacon's map, 522.
Clement VII (1523–34), Pope, *and* land drainage, 311; *and* medals, 338–9.
Clement, William (*fl* 1677–99), inventor of anchor-escapement, 658, 664–5.
Cleostratus (*c* 542 B.C.), *and* Greek calendar, 570.
Clerville, L.-N. de (d 1677), chief royal engineer to Louis XIV of France, 466.
Cock, Christopher (*fl* 1660–96), instrument-maker, 234, 635.
Coehoorn, M. (1634–1704), military engineer, 372.
Coke, Thomas William, of Holkham (1752–1842), agriculturist, 15.
Colbert, J. B. (1619–83), French statesman, *and* canals, 464–6; *and* cloth calender, 178; *and* textile factory, 152, 711; *and* tinplate, 689; *and* Venetian glass-makers, 238.
Cole, Humfray (? 1530–91), engraver and die-sinker, mathematical instrument-maker, 586.
Columbus, Christopher (? 1446–1506), navigator, 477, 548–9; *and* maize, 3; *and* tobacco, 8.
Constantine I the Great (312–37), Roman emperor, *and* rebuilding of Constantinople, 279.
Contarini, G. M. (*c* 1506), cartographer, 535.
Cook, Captain James (1728–79), navigator, 557.
Copernicus (1473–1543), astronomer, 589.
Corneille, T. (1625–1709), author of *Dictionnaire des arts et des Sciences*, 682.
Corneliszoon, Cornelis, of Uitgeest (*fl* end of sixteenth century), engineer, *and* saw-mill, 106; *and* drainage-mill with centrifugal pump, 307–8.
Corobus (*c* 776 B.C.), victor in Olympic Games, 572.
Corsini, Ottavio (*c* 1625), hydraulic engineer, 314–15.
Cort, Henry (1740–1800), ironmaster, 81.
Cortes, Martin (1532–89), author of navigation manual, 548.
Cortez, Hernando (1485–1547), explorer, *and* cacao-bean, 6; *and* cochineal, 695.
Cosimo I de' Medici (1537–63), Grand Duke of Tuscany, treasure-room in Palazzio Vecchio, Florence, 707.
Cosnier, Hugues (d 1629), canal-engineer, 460–3.
Coster, Laurens (*fl* 1440) of Haarlem, printer, 377, 383.
— Salomon da (seventeenth century), clock-maker to Huygens, 663.
Cramer, J. A. (*c* 1739), assayer, 60.
Crapponne, Adam de (1526–76), canal-engineer, 459.
Crates the Grammarian (*c* 165 B.C.), *and* map of the world, 518; *and* terrestrial globe, 614.
Cresques, Abraham (*fl c* 1370–80), chart- and compass-maker to the king of Aragon, 544.
Cresy, Edward (1792–1858), author of 'Encyclopaedia of Civil Engineering' (London, 1847), 428, n 2.
Crisp, Sir Nicholas (*c* 1599–1666), *and* new inventions and processes, 680, 686.
Cromwell, Oliver (1599–1658), *and* copper coins, 46; *and* cavalry tactics, 349.
Croone, William (1633–84), physician, 59.
Ctesibius (? *c* 100 B.C.), *and* water-clock, 601–2.
Cubitt, Sir William (1785–1861), engineer, 101.
Culpeper, Edmund (1660–1738), microscope-maker, 635.
Cuthbert, St (? 635–87), bishop of Lindisfarne, fragments of fabric found in tomb of, 197.
Cyrus the Great (558–529 B.C.), king of Medes and Persians, conqueror of Babylon, 567.

Dampier, William (1652–1715), sea captain, 499.
Dangon, Claude (*fl* 1605–20), Lyons weaver, inventor of lever draw-loom, 165, 189.
Danisy (*c* 1732), *and* structure of arches, 434.
Danner of Nuremberg (*c* 1550), printer, 337.
Darby family, *and* use of coal in iron industry, 689.
Davis, John (d 1605), explorer and navigator, 522, 625.
Deane, Sir Anthony (? 1638–1721), shipwright, 482, 488.
Debaufe, Jacob (*c* 1704), watchmaker, 671.
— Peter (*c* 1704), watchmaker, 671.
Dee, John (1527–1608), mathematician, *and* scientific instruments, 231, 586.
Deinocrates (*fl* 336–323 B.C.), architect to Alexander the Great, 275.
Deloney, Thomas (? 1543–? 1607), author of 'Pleasant History of John Winchcombe', 151.
Demachy, J. F. (1728–1803), author of treatise on hydrometer, 22.
Dereham, Richard (*c* 1678), mechanician, 162.

Desaguliers, John Theophilus (1683–1744), *and* steam boiler, 687.
Descartes, René (1596–1650), philosopher, 5, 232, 234.
Darius I (521–485 B.C.), Persian king, *and* canals, 439.
Dicaearchus (*fl c* 300 B.C.), pupil of Aristotle, *and* map of the world, 505.
Dicas, John (*c* 1780), inventor of hydrometer, 22.
Diderot, D. (1713–84), philosopher, 89, 113, 116, 360, 367.
Digges, Leonard (1510–58), mathematician, *and* scientific instruments, 231, 541–2, 586.
— Thomas (*c* 1543–95), mathematician, *and* theodolite, 541.
Dio Cassius (third century A.D.), Roman historian, *and* Egyptian calendar, 565.
Dionysius Exiguus (*c* 530), Scythian monk, *and* chronology of the Christian era, 578.
Dircxz, William (*c* 1604), inventor of Dutch ribbon-looms, 167.
Divini, Eustachio (1620–95), manufacturer of lenses, 234.
Dodson, William (*fl* second half of seventeenth century), hydraulic engineer and author of 'Designe for the perfect draining of the Great Level of the Fens' (1665), 321.
Dodson (middle of eighteenth century), *and* navigation charts, 555.
Dollond, John (1706–61), instrument-maker, *and* achromatic lens, 233, 555.
Domenico da Viterbo, the brothers (*c* 1481), canal-engineers, 446, 451 n.
Donald, David (*c* 1727), mechanician, 157.
Dondi, Giovanni de (*fl* 1318–?80), *and* astronomical clock, 653–5, 658.
Donkin, Bryan (1768–1855), inventor, 416.
Dossie, R., author of 'The Handmaid to the Arts' (1758), 226, 229.
Drake, Sir Francis (? 1540–1596), *and Golden Hind*, 477, 494; *and* rust-preventing pitch, 679.
Drebbel, Cornelius (1573–1633), comprehensive inventor, 679–80, 695.
Dritzehn, Andreas, of Strasbourg (*c* 1436), printer, partner of J. Gutenberg, 384.
Duarte (Edward) (1433–8), king of Portugal, *and* pocket sun-dial, 533.
Dubie, Maître (seventeenth century), canal-engineer, 454.
Dudley, Sir Robert (1574–1649), *and* quadrant with a nonius, 640.
Dummer, Edmund, Surveyor to the Navy 1692–8, 484.
Dürer, Albrecht (1490–1538), artist, 370, 407.

Edward the Confessor (1042–66), English king, fabric from the tomb of, 198.
Edward I (1272–1307), English king, *and* town-planning, 283–4.
Edward VI (1547–53), English king, *and* coinage, 46.
Edwards, William (1719–89), builder of the Pont-y-ty-Prydd, 435–6.
Eele, Martin (seventeenth century), patentee of 'British Oil', 688.
Egmond, Count Van (1522–68), *and* land reclamation, 302.
Elizabeth I (1558–1603), English queen, *and* restoration of coinage, 46; *and* town planning, 295.
Ellyott, William (*c* 1614), metallurgist, 79.
Épernon, Duc d' (*c* 1628), *and* drainage of Gironde marshes, 319.
Eratosthenes (*c* 275–*c* 194 B.C.), librarian of Alexandria, *and* cartography, 505–7, 509 n 1, 522, 547.
Ercker, Lazarus (d 1593), metallurgist, 28, 34, 37, 41, 50, 53, 59, 60–3, 65, 67–8.
Erlinger, Georg (d 1542), of Augsburg, printer and engraver of maps, 535.
Estienne, Charles (1504–64), *and* agriculture, 13.
Etzlaub, Erhard (*c* 1492) of Nuremberg, maker of compass-dial and road map, 534–6.
Eudoxus (*c* 370 B.C.), *and* form of the Earth, 504.
Eutropius (fourth century), Roman historian, *and* Roman calendar, 575.
Evans, Oliver (1755–1819), engineer, 16, 19.
Evelyn, John (1620–1706), diarist, 77, 291, 296–8, 491, 681, 686, 696.

Fabrizio, Geronimo (1537–1619), *and* spectacle lenses, 231.
Faccio de Duillier, Nicholas (1664–1753), mathematician, 670–1.
Falcon (*c* 1728), mechanician, 166.
Falda, Giovanni Battista (? 1640–? 1700), engraver, 312–13.
Fantoni (*c* 1630), hydraulic engineer, 314.
Fell, John (1625–86), *and the* Clarendon Press, Oxford, 402.
Fenizi, Ascania (*c* 1586), hydraulic engineer, 311.
Ferdinand, Grand Duke of Tuscany (*c* 1623), *and* land drainage, 314.
Féron, of Paris (*c* 1895–1950), maker of wooden tools, 115.
Filastre, Cardinal Guillaume, of Rheims (fifteenth century), *and* maps, 532–3.
Finiguerra, Maso (1426–64), of Florence, engraver, 406.
Flabianus, Petrus (*c* 1090), glass-maker, 209.
Flamsteed, John (1646–1719), first Astronomer Royal, *and* astronomical tables, 552, 667.

Fontaine, Jean (*fl* early seventeenth century), canal-engineer, 460.
Fontana, Carlo (1634–1714), architect, 248.
— Domenico (1543–1607), architect, 289.
Foullon, Abel (1513–63), mathematician, *and* plane-table survey, 540.
Fourdrinier, Henry (1766–1854) *and* Sealy (d 1847), stationers, 416.
Francesco I de' Medici (1574–87), Grand Duke of Tuscany, *and* glass-furnace, 217; *and* paintings from the Palazzo Vecchio, 707.
Francini (*c* 1628), canal-engineer, 462.
Franciscus Paduanius of Forli (1543–16—?), physician to Emperor Rudolph II, *and* scientific instruments, 621.
François I (1515–47), French king, *and* town-planning, 290; *and* canals, 449, 459.
Fratta et Montalbano, Marchése della (*c* 1678), metallurgist, 50.
Frederick the Great (1740–86), Prussian king, *and* potato cultivation, 2.
Frederick William (1640–88), the Great Elector of Brandenburg, *and* canals, 454; *and* laboratory and glass-works, 682.
Frisi, Paolo (1728–84), mathematician, 315.
Fromanteel (seventeenth century), clock-making family, 663.
Fuchs, Leonhart (1501–66), herbalist, 4.
Fust, Johann (*c* 1400–*c* 1466), goldsmith and printer, 377, 383–6.

Gabriel, Jacques (IV) (1630–86), architect, 425.
— Jacques (V) (1667–1742), architect, 425 n.
— Jacques (VI) (1698–1782), architect, 425 n.
Gaddi, Taddeo (? 1300–66), bridge designer, 428.
Galantier (*c* 1687), French mechanician, 165.
Galen (? 129–99), physician, *and* humoral theory, 24.
Galilei, Galileo (1564–1642), *and* assaying balances, 67; catenary curve, 258; hydraulic engineering, 303, 313–15; laws of motion applied to projectiles, 374; lens-grinding, 234; mechanics, 252; microscopes and telescopes, 231–2, 552, 631, 634; pendulum, 662–3; sector, 627–8; ship-building and pump-making techniques, 432; strength of materials, 58–9, 252, 432; the vacuum, 332, 344.
— Vincenzio (seventeenth century), son of the above, *and* pendulum, 662.
Gamble, John (early nineteenth century), stationer, 416.
Gascoigne, William (? 1612–44), inventor of micrometer, 640.
Gautier, Henri (1660–1737), bridge builder, 429, 436.
Gemini, Thomas (*fl* 1524–62), mathematical instrument-maker, 586, 621.
Geminus, *and* Greek calendar, 570.
Gemma, Reiner, Frisius (1508–55), professor of mathematics at Louvain, *and* astrolabes, 586; *and* Gerard Mercator, 550; *and* Jacob's staff, 591; *and* measurement of longitude by portable chronometer, 503; *and* triangulation, 539.
Gennes, M. de (*c* 1678), French naval officer and mechanician, 168–9.
George III (1760–1820), English king, collection of scientific instruments, 645.
Gerard, John (1545–1612), herbalist, 1, 3.
Gerard of Cremona (? 1114–1187), *and* tables of latitude and longitude, 521; *and* translation of Ptolemy's *Almagest*, 585.
Gerbert (Pope Sylvester II, 999–1003), *and* astrolabe, 609; *and* geometric square, 608; *and* sighting-tubes, 594–5.
Gerritszoon, Jan (*c* 1596), hydraulic engineer, 318.
Gerson, Levi ben (1288–1344), mathematician, *and* Jacob's staff, 528, 546, 591.
Gilpin, George (*c* 1794), scientist, *and* tables of gravities for use with hydrometer, 22.
Giordano of Pisa (*c* 1306), Friar, *and* reference to eye-glasses, 230.
Glaser, Christoph (d *c* 1671), chemist, 682.
Glauber, Johann Rudolph (1604–68), chemist, 37, 40, 43–4, 52, 55–6, 58, 68, 682, 685, 719.
Gluck, Jean (*c* 1660), dyer, 695.
Gohory, Jacques (d 1576) of Paris, physician, advocate of tobacco as a cure-all, 8.
Goldenberg et Cie (*c* 1875), Alsatian tool-making firm, 117.
Gonzaga, Charles of (*c* 1606), Duke of Mantua and Nevers, Governor of Champagne, founder of Charleville (Ardennes), 290.
Graham, George (1673–1751), clock-maker, scientific instrument-maker, 553–4, 557, 641, 665, 671, 673.
Greenwood, Frans (*c* 1722), glass-engraver, 229.
Gregory XIII (1572–85), Pope, *and* reform of calendar, 577–9.
Gregory, James (1638–75), mathematician, *and* clocks, 667; *and* reflecting telescope, 552 n.
Griffiths, Hannah, of Norwich (*c* 1850), maker of wooden tools, 115.
Grosseteste, Robert (*c* 1175–1253), bishop of Lincoln, *and* optical theory, 230.
Grubenmann, Hans Ulrich (*c* 1757), engineer and bridge builder, 427–8.
Guarini, Guarino (1624–83), architect, 254.
Guericke, Otto von (1602–86), *and* vacuum pump, 637.

Guglielmini, Domenico (*c* 1697), hydraulic engineer and author of book on 'The nature of rivers', 315.
Guise, Duc de (1550–88), armour of, 353.
Gunter, Edmund (1581–1626), mathematician, inventor of 'Gunter's line', 542.
Gustavus Adolphus (1611–32), Swedish king, *and* cavalry tactics, 349.
Gustavus Vasa (1523–60), Swedish king, *and* blast furnaces, 31; *and* canals, 455.
Gutenberg, John (*c* 1400–*c* 1467), goldsmith and printer, 44, 377, 381, 383–5.
Guyldforde, Sir Richard (? 1455–1506), Henry VII's master of the ordnance, *and* galleys, 473.
Guyon, Jacques (*c* 1638), canal-engineer, 463.

Habermel, Erasmus, of Prague (*fl* last part of sixteenth century), scientific instrument-maker, 621.
Habrecht, Isaac (*c* 1574), clock-maker, 656.
Hadley, John (1682–1744), mathematician, 458; *and* quadrant, 555–6.
Haines, Richard (*c* 1678), mechanician, 162.
Hakluyt, Richard (? 1522–1616), author of 'Principal Navigations', 477.
Hall, Chester Moor (1703–71), *and* achromatic lenses, 233, 633.
Halley, Edmond (1656–1742), Astronomer Royal, 499, 544, 555.
Hanbury, John (*c* 1730), *and* tinplate, 689.
Handson, Ralph (*c* 1614), instructor in navigation, 551.
Harriot, Thomas (1560–1621), mathematician and astronomer, *and* tobacco, 9; *and* navigation charts, 551.
Harris, John (? 1667–1719), author of *Lexicon technicum*, 682.
Harris, Walter (1647–1732), scientist, *and* chemical notion of disease, 24.
Harrison, James (?1697–? 1767), clockmaker, 670, 672.
— John (1693–1776), clockmaker, 503, 557, 670, 672.
Harrison, William (1534–93), author of 'An historicall description of the Islande of Britaigne', 43.
Hartlib, Samuel (*c* 1599–*c* 1670), *and* agriculture, 677; *and* German mining and metallurgy, 678; *and* new inventions and processes, 680–1.
Hartmann, Georg, of Nuremberg (1489–1564), *and* calculating device, the nocturnal, 615.
Hatton, Sir Christopher (1540–91), Lord Chancellor, crest of, 494.
Hauksbee, Francis (1687–1763), *and* vacuum pump, 637–8.
Hawke, Lord (1705–81), Admiral, 499.
Henckel, Johann Friedrich (1679–1744), chemist, 30.
Hennell, T., author of 'The Countryman at Work' (1947), 111.
Henri II (1547–59), French king, *and* coinage, 341.
Henri IV (1589–1610), French king, *and* machine-knitting industry, 185; *and* town-planning, 293; *and* land reclamation, 318–19; *and* canals, 459–61, 464.
Henry II (1002–24), emperor, robe of, 198.
Henry V (1413–22), English king, damask attached to shield of, 203.
Henry VI (1190–7), emperor, robe from tomb of, 198.
Henry VII (1485–1509), English king, *and* ships, 497.
Henry VIII (1509–47), English king, *and* coinage, 46; *and* Artillery Company, 351; *and* sporting-guns, 358; *and* ships, 471, 478, 480.
Henry the Navigator (1394–1460), Portuguese prince, 477, 544.
Heraclius (? tenth century), possible author of *De coloribus et artibus Romanorum*, 207.
Hercules, mythical Greek hero, traditional founder of Olympic Games, 572.
Hermannus Contractus ('the Lame'), abbot of Reichenau (*c* middle of eleventh century), author of *De mensura astrolabii*, 609.
Hero of Alexandria (*fl c* A.D. 62), mechanician, 334, 512, 609–12, 618, 641.
Herodotus (*c* 484–425 B.C.), Greek historian, 270–1, 526.
Herschel, William (1738–1822), astronomer, 233, 237.
Hesse, Esban (*c* 1532), ironworker and writer on rolling-mills, 342.
Hevelius, Johann (1611–87), Danzig astronomer, *and* optical instruments, 236, 625, 640.
Hexham, John (*fl* late sixteenth century), surveyor, 317.
Hezekiah (*c* 715–*c* 687 B.C.), king of Judah, *and* surveying, 510.
Higgs, J. W. Y., Keeper of the Museum of English Rural Life, Reading, 149.
Hill, Abraham (1635–1721), 157.
Hipparchus (*fl* 161–126 B.C.), astronomer, 506, 517, 559, 564, 571, 583, 586–7, 591, 603, 612.
Hippocrates (*c* 400 B.C.), Greek physician, *and* calendar, 569.
Hippodamos of Miletos (fifth century B.C.), Greek town-planner, 272–3.
Hjärne, Urban (1641–1724), president of *Bergcollegiums*, Stockholm, superintendent of Charles XI's technical laboratory, 682.

Hochstetter, Daniel (sixteenth century), German mining expert, 63.
Hofmann, J. J. (1635–1706), scholar, 682.
Hogarth, William (1697–1764), English painter, 11, 120.
Holbein, Hans (1497–1543), portrait painter, 586.
Holden, Richard (*c* 1732), Irish bleaching expert, 176.
Homberg, Wilhelm (1652–1715), chemist, 683.
Home, Francis (1719–1813), physician, 176.
Honnecourt, Villard de (*c* 1250–*c* 1300), architect, *and* escapement in clock mechanism, 648–9.
Hooke, Robert (1635–1703), scientist, 35, 41, 45, 55–7, 252, 256–7, 297–8, 555, 631, 635, 640, 669, 681.
Hooper, Stephen (*c* 1789), millwright, 100–1.
Hore, John (*c* 1690–1762), canal-engineer, 457.
Houghton, John (d 1705), editor of 'A Collection for the Improvement of Husbandry and Trade', 43, 682.
Howard, Charles (1536–1624), of Effingham, Lord High Admiral 1585–1618, 481.
Hulsbos, Symon, of Leiden (*c* 1634), inventor of screw with fixed casing, 305.
Hummel, Hans, of Basel (*c* 1730), inventor of water-driven ribbon-loom, 168.
Hunt, William, & Son (*c* 1905), tool-makers, 116.
Huntsman, Benjamin (1704–76), metallurgist, 35.
Huygens, Christiaan (1629–95), scientist, 232, 234, 236, 344–5, 375, 543, 552, 637, 662–6, 668–9.

Ibn al-Haitham (Alhazen) (*c* 965–*c* 1039), writer on optics, 230.
Ibn al-Nabdī (*c* 1043), *and* silver globe in library at Cairo, 613.
Ibn al-Zarqālī (Arzarchel) (twelfth century), *and* tables of latitude and longitude, 521.
Ideler, C. L., author of *Handbuch der mathematischen und technischen Chronologie*, Berlin, 1825, 564.
Innocent XI (1676–89), Pope, *and* draining of marshes, 312.
Innocent XII (1691–1700), Pope, *and* river-bank construction, 313.
Isidore, St (? 560–636), author of *Etymologiarum libri VII*, *and* shape of the Earth, 519; *and* meridian, 522.

James I (1603–25), English king, author of 'Counterblast to Tobacco', 9; *and* town-planning, 295.
James, Duke of York, later James II (1685–9), English king, *and* rebuilding of London after Great Fire, 297.
Janssen (*or* Jansen), Johannes (*c* 1634), *and* record of spectacle-making, 231.
Jars, Gabriel (1732–69), mineralogist, 86.
Jenson, Nicolas (d *c* 1480), printer, 384.
Jevons, W. S. (1835–82), economist, 87.
Joachim II (*c* 1540), Elector of Brandenburg, *and* canals, 454.
John, Prince, later King John II (1481–95) of Portugal, *and* navigation, 547.
John Campanus of Novara, *see* Campano da Novara.
John of Linières (*fl* 1320–50), astronomer, 585, 616.
John of Northampton, *and* calculating device, 614.
Jones, Inigo (1573–1652), architect, 256–7, 265, 267, 295.
Josse, St (d 669), legendary king of Brittany, *and* 'Elephant' silk, 191.
Jousse, Maturin (*c* 1627), metallurgist, 33, 36, 57, 89, 92, 106.
Julius II (1503–13), Pope, *and* town-planning, 288; *and* seals and medals, 338.
Jürgen, Master (*c* 1530), mason of Brunswick, supposed inventor of the treadle for spinning-wheels, 160.

Kalthoff, Caspar (*c* 1628), German gunfounder, 680.
Kay, John (*fl* 1733–64), inventor of the flying-shuttle, 153, 161, 168–70.
Keltridge, William (*c* 1684), *and* drawing of ship, 490.
Kendall, Larcum (1721–95), clock-maker, 557.
Kepler, Johann (1571–1630), astronomer, 232, 640, 658.
Kidinnu *or* Kidenas (*c* 383 B.C.), Chaldean astronomer, *and* Babylonian calendar, 568, 574.
Knibb, Joseph (*c* 1673), London clock-maker, 667.
Knight, Dr Gowin (1713–72), *and* mariners' compasses, 555.
Koops, Matthias (*c* 1800), paper-maker, 415.
Kotter (or Kutter) (*c* 1520) of Nuremberg, gunsmith, 358.
Kratzer, Nicolas (1487–? 1550), mathematician, 586.
Kublai Khan, Emperor of China (1259–94), *and* paper currency, 379–80.
Kuffler, Abraham, Gilles, Jacob, Johannes (seventeenth century), dyers, 695.
Kunckel, Johann (Baron Löwenstjern) (1630–1703), metallurgist, author of *Ars vitraria experimentalis*, 55, 218, 222, 224–5, 229, 682–3, 696–8.

Labelye, Charles Dangeau de (1705–? 81), architect, 425.
La Hire, Philippe de (1640–1718), author of *Traité de mécanique, and* theory of the arch, 433–4; *and* survey-instruments, 543.
Lamberville, C. (*c* 1638), author of a tract on canal-building, 86.
Lavoisier, Antoine Laurent (1743–94), chemist, 25.
Lee, Edmund (*c* 1745), millwright, 98.
— William (d *c* 1610), inventor of frame-knitting machine, 185–6.
Leeghwater, Jan Adriaanszoon (1575–1650), hydraulic engineer, 303, 305–7, 319.
Leeuwenhoek, A. van (1632–1723), scientist, *and* lens-grinding, 232–4; *and* microscope, 631, 633.
Leicester, 1st Earl of (1532–88), *and* land drainage, 304.
— Earl of (*c* 1631), *and* houses in Leicester Square, 296.
Lemercier, Jacques (1585–1654), architect, 291.
Lémery, N. (1645–1715), chemist, 682, 696.
Leo X (1513–21), Pope, *and* town-planning, 288; *and* land drainage, 311.
Leonardo da Pisa (?1180–?1250), *and* portable quadrant, 599, 608.
Leonardo da Vinci (1452–1519), universality, 250, *and* arches, 432–3; building, 250–2; canals, 447–8, 450, 459; clocks, 657; dynamics, 344; furnaces, 54; gig-mills, 172; hodometer, 512–13; hydraulic engineering, 286, 311; lock mitre-gates, 447–8; machines for working metallic mirrors, 236; metallurgy, 39–41; military engineering, 285, 370; minting techniques, 47, 340–1; roasting devices, 20; roller-bearings, 327; screws, 335, 657; shearing-machine, 174–5; spinning-machinery, 161; strength of materials, 250–2, 432–3; town-planning, 285–6; turret windmill, 330; weaving-loom, 167.
Lepaute, Jean André (1727–1802), French clock-maker, 674.
Leroy, Julien (1686–1759), horologist, 557.
— Pierre (1717–85), horologist, 557, 674.
Lescot, P. (1510–78), architect, 253.
Lethaby, W. R., author of 'Medieval Art', 240.
Li Yueh (*c* 1283), Chinese canal-engineer, 440.
Libavius, Andreas (1540–1616), chemist, 30.
Linnaeus, Carl (1707–78), Swedish botanist, 6, 159.
Linperch, P. (*c* 1727), Swedish writer on windmills, 89.
Lippmann, E. O. von (*c* 1930), *and* type-metal, 44.
Lister, Martin (? 1638–1712), *and* zaffre, 703.
Lobsinger, Hans, of Nuremberg (*c* 1550), inventor of wooden box-bellows, 32.
Locquenghien, Jean de (1518–74), canal-engineer, 452.
Löhneiss, Georg Engelhard von (*c* 1617), German metallurgist, 28, 51.
Lorini, Buonaiuto (*c* 1592), architect and town designer, 286.
Louis IX (1226–70), French king, and town-planning, 283.
Louis XIII (1610–43), French king, *and* town-planning, 293; *and* canals, 463.
Louis XIV (1643–1715), French king, *and* town-planning, 290, 293; *and* canals, 465–6.
Louis XV (1715–74), French king, *and* geodetic expeditions, 553.
Löwenstjern, Baron, *see* Kunckel.
Lu Ch'ih (*c* 1283), Chinese canal-engineer, 440.
Lübeck, Petter von (*c* 1610), canal-engineer, 455.
Lud, Walter (*fl* last part of fifteenth and early sixteenth centuries), cartographer, 538.
Lull, Ramón (? 1235–1315), alchemist, author of *Arbor Scientiae, and* navigation, 526.
Lupicini, Antonio (*c* 1530–98), hydraulic engineer, *and* author of books on hydraulics, 310–11.

Machiavelli, Niccolò (1469–1527), *and* fortification, 370.
Macrobius (fifth century), grammarian, *and* Roman calendar, 575.
Maertense, Willem (*c* 1554), canal-engineer, 453.
Magellan, Ferdinand (? 1480–1521), navigator, 4, 477.
Magellan (*c* 1780), distiller, 12.
Mainz, John of (*c* 1477), typefounder, 393.
Mandeville, Bernard (? 1670–1733), author of 'The Fable of the Bees', *and* inventions, 706.
Mansart *or* Mansard, François (1598–1666), architect, 253, 255.
Mansart, J. Hardouin- (1646–1708), architect, 254–5, 425.
Månsson, Peder (*fl* 1508–24), Swedish metallurgist, author of *Glaskonst* ('Art of Glass'), 28, 40, 209–10, 212, 214, 220.
Mantoux, Paul, historian, *and* coal, 85.
Marco Polo (? 1254–? 1324), explorer, *and* coal, 73; *and* printing in Far East, 379; *and* China and Japan, 524.
Marggraf, Andreas Sigismund (1709–82), chemist, 30.
Marino, Ieronimo (*c* 1545), engineer, 290.
Marinus of Tyre (*c* A.D. 120), *and* cartography, 507–9.
Mariotte, Edmé (1620–84), physicist, 464.

Markham, Gervase (? 1568–1637), author of 'Farewell to Husbandry', 134–5.

Marlborough, John Churchill, first Duke of (1650–1722), 347, 350.

Marshall, John (1663–1725), microscope-maker, 633–4.

Marshall, William (1745–1818), agriculturist, 15.

Martini, Francesco di Giorgio (*c* 1500), architect, 286.

Maskelyne, Nevil (1732–1811), Astronomer Royal, 557.

Mason, Joseph (*c* 1687), mechanician, 165.

Mathesius, Johannes (sixteenth or seventeenth century), *and* information on metallurgy, 28.

Matignon, Mareschal de (*c* 1587), *and* land reclamation near Bordeaux, 318.

Maupertuis, P. L. Moreau de (1698–1759), mathematician, *and* measurement of arc of the meridian, 553.

Maurice, Prince, of Nassau (1618–25), Stadtholder in Holland, *and* land drainage, 304, 306; *and* cavalry tactics, 349.

Mauro, Fra (*c* 1459), cartographer, 530.

Maurolico, Francesco (1494–1575), *and* spectacle lenses, 231.

Maximilian I (1493–1519), Emperor, *and* armour, 352–3.

Maximilian I, Elector of Bavaria (1623–51), *and* rifles, 358.

Maydwell and Windle (*c* 1775), glass-dealers, 225.

Mazzoleni, Marcantonio (*fl c* 1600), Galileo's workman, 627.

Meda, Giuseppe (*c* 1540–99), canal-engineer, 449.

Medici, Giuliano de' (1479–1516), patron of Leonardo da Vinci, 311.

Medina Sidonia, Duke of (1550–1615), commander of Spanish Armada 1588, 480.

Meijer, Cornelis Janszoon (*fl c* 1670–80), hydraulic engineer and author of books on technology, 312–14.

Meikle, Andrew (*c* 1772), millwright, 98, 100–1.

Melckenbeke, Dominicus van, of Middelburg (*c* 1598), inventor of archimedean pump, 305.

Meldolla, Andrea (1522–82), artist, 407.

Mercator, Gerard (1512–94), cartographer, 536, 550, 586.

Mercier, Le (*c* 1628), canal-engineer, 462.

Merret (*or* Merrett), Christopher (1614–95), metallurgist, 37, 41, 218–21, 681–2, 698.

Mersenne, Marin (1588–1648), philosopher, 49 n 1, 58.

Mersey, Mathias (*c* 1614), metallurgist, 79.

Mesrell (sixteenth century), French workman condemned for counterfeiting coins, 341.

Messahala (Mesahallah, Māshāllāh) of Basra (*c* 762), writer on the astrolabe, 529, 609.

Mestrell, Eleye (sixteenth century), French workman condemned for counterfeiting, 341.

Meton (*c* 432 B.C.), *and* calendar, 568, 570.

Michelangelo (1475–1564), 246, 248, 289.

Mills, Peter, designer of plan (lost) for rebuilding of London after Great Fire of 1666, 297. [223.

Miseroni, Dionisio (*c* 1653), glass-engraver,

Missaglia, Benedetto da (*c* 1518), canal-engineer, 448–50. [445.

Modena, Filippo da (*c* 1438), canal-engineer,

Moll, Tilleman de (*fl* end of seventeenth century), canal-engineer, 455.

Möller, Anton, of Danzig (*c* 1586), inventor of mechanical loom, 167.

Monconys (*c* 1663), *and* 'athanor', automatic furnace, 680.

Monte Corvino, Archbishop John of (*c* 1306), missionary, *and* printing, 380.

Moreton, Charles (*c* 1692), mechanician, 157.

Morley, Thomas (1557–*c* 1603), composer and publisher of music, 409.

Morrice (or Morris), Peter (*c* 1580), hydraulic engineer, 317.

Mortimer, John (*c* 1707), author of 'The Whole Art of Husbandry', 134.

Mountaine (middle of eighteenth century), *and* navigation charts, 555.

Moxon, Joseph (1627–1700), metallurgist, author of manual on printing, and of 'Mechanick Exercises', 35, 44, 116, 385, 391–6, 401.

Mudge, Thomas (1760–1843), clock-maker, inventor of lever-escapement, 673–4.

Muhammad (*c* 570–632), Prophet of Islam, *and* Islamic calendar, 580.

Muhammad ibn Qala'un (1293–1341), Mameluke sultan, *and* satin damask, 203.

Münster, Sebastian (1489–1552), author of *Cosmographia*, *and* survey instruments, 540.

Musschenbroek, Pieter van (1692–1761), scientist, 59.

Nabonassar (*c* 747 B.C.), founder of Babylonian kingdom, *and* chronology, 564–6.

Napier, John (1550–1617), mathematician, 58.

Nash, Isaac, modern tool-maker, 116.

Nāṣir al-Dīn al-Ṭūsī (1201–74), founder of observatory at Marāgha, 584.

Nebuchadrezzar (605–561 B.C.), Babylonian king, *and* ancient Babylon, 270.

Neckam, Alexander (1157–1217), *and* navigation, 523.

Needham, Joseph, author of 'Science and Civilisation in China' (1954), *and* coal in China, 73–4.

Nehou, Lucas de (*c* 1676), glass-maker, 238.

Neri, A. (*c* 1612), author of *L'Arte vetraria*, 41, 217–19, 221, 229, 681–2, 698.

Neugebauer, O., author of 'The Early History of the Astrolabe' (1949), 564, 603.

Neumann, Caspar (1683–1737), chemist, *and* zinc, 692.

Newton, Isaac (1642–1727), 41, 232–4, 344, 375, 552 n, 553, 555, 632–4, 644–5.

Nicholas of Cusa (1401–64), Cardinal, mathematician, *and* astronomical instruments, 585; *and* lenses, 231; *and* maps, 533.

Nicholaus Germanus (Donis), Dominus (*c* 1462), miniaturist, *and* maps, 531–2.

Nicot, Jean (? 1530–1600), French Ambassador in Portugal, *and* tobacco and snuff, 8, 10.

Niquet, Antoine (1639–1724), canal-engineer, 467, 468 n.

Norwood, Richard (*c* 1590–1675), cartographer and surveyor, 544, 550.

Novate, Bertola da (*c* 1410–75), canal-engineer, 445–6.

Numa, second king of Rome, *and* calendar, 575.

Nuñez, Pedro (1492–1577), mathematician, *and* navigation charts, 548.

Nūr al-Dīn (?1118–74), Sultan, *and* sundial, 596.

Oeglin, Erhard (*c* 1508), of Augsburg, music printer, 406.

Oldenbarnevelt, Johann Van (1547–1619), Dutch statesman, *and* land reclamation, 302.

Opnaim, Mayer (*c* 1755), glass-maker, 229.

Orme, Philibert de l' (?1510–70), French architect, 253–4, 266.

Orosius (fifth century), author of 'History of the World', 518.

Ortell, Joachim (*c* 1584), emissary from Dutch States-General, *and* land drainage, 317.

Oughtred, William (1575–1660), mathematician, 631.

Ovid (43 B.C.–A.D. 17), Roman poet, *and* Roman calendar, 575.

Pace, Girolamo di (*c* 1558), hydraulic engineer, 310.

Pacioli, Luca (1445–1509), mathematician, 250.

Paeonius (*c* A.D. 410), recipient of letter supposedly relating to astrolabe, 603.

Palissy, Bernard (*c* 1510–*c* 90), potter, writer of books on gardening and town-planning, author of *L'Art de la Terre*, 290, 678–9.

Palladio, Andrea (1518–80), architect, 417, 426–7, 429.

Palmer, William (*fl* 1726–32), canal-engineer, 458.

Panciroli, Guido (1523–99), professor of civil law at Padua, author of books on lost arts and new inventions, 677.

Pantheus, J. A. (*c* 1530), metallurgist, 27, 29, 40–1, 47–8.

Papin, Denys (? 1647–1712), *and* use of steam, 687; *and* vacuum pump, 637.

Pappus, commentator on Ptolemy's *Almagest*, 586, 590–2.

Paracelsus, Theophrastus Bombastus von Hohenheim (? 1493–1541), physician, 29, 30 *and* n, 690.

Paré, Ambroise (? 1517–90), surgeon, 374.

Parker, R. A., author of 'The Calendars of Ancient Egypt', 561–5.

Parma, Duke of (late seventeenth century), *and* hydraulic engineering, 315.

Pascal, Blaise (1623–62), *and* analysis of the vacuum, 332; *and* barometer, 543; *and* calculating-machines, 627.

Paul, Lewis (d 1759), inventor of carding-machines, 153–4, 162–3.

Paul III (1447–64), Pope, *and* town-planning, 288.

Paul IV (1555–9), Pope, *and* town-planning, 288.

Paul V (1605–21), Pope, *and* town-planning, 289.

Paulus Alemannus (*c* 1477), *and* description of fusee of clock, 657.

Pelling, London apothecary, 5.

Pepys, Samuel (1633–1703), diarist, 5–6, 297, 358, 488, 490.

Peregrinus, Peter, of Maricourt, Picardy (*c* 1269), *and* boxed compasses, 524.

Pericles (*c* 495–429 B.C.), Greek statesman, *and* town-planning, 272.

Perrault, Claude (1613–88), anatomist and architect, 256; *and* steel, 58.

Perronet, Jean Rodolphe (1708–94), bridge designer, 428–9, 436.

Perrot, Bernard, of Orleans (*c* 1668), glass-maker, 225.

Perrott, Humphrey, of Bristol (*c* 1734), glass-maker, 226.

Perry, Captain John (*c* 1715), hydraulic engineer, 422.

Peruzzi, B. (1431–1536), architect, 288.

Peter IV, the Ceremonious (1336–87), King of Aragon, *and* navigation, 544.

Peter the Great (1682–1725), Russian Emperor, *and* canals, 453.

Petrucci (*c* 1501), of Venice, music printer, 406.

Pett, Peter (1610–? 70), commissioner of the navy, 485.

— Phineas (1570–1647), shipbuilder, 485.

Pettus, Sir John (1613–90), *and* metals and chemistry, 677.

Petty, William (1623–97), *and* new inventions and processes, 681; *and* dyeing, 692–5.
Pfister, Albrecht (*c* 1460), of Bamberg, printer, 405.
Philoponus (*c* A.D. 530), author of text on plane astrolabe, 603, 605–6, 608.
Picard, Jean (1620–82), *and* survey-instruments, 543–4, 553–4; *and* astronomical tables, 557.
Pieters, Pieter (*c* 1605), hydraulic engineer, 306.
— William (*c* 1605), hydraulic engineer, 306.
'Pincher Jack' (*c* 1890), travelling smith, 113–14.
Pitentino, Alberto (*fl c* 1188–98), canal-engineer, 442.
Pius IV (1559–66), Pope, *and* town-planning, 288.
Plantin, Christophe (1514–89), printer, author of *Dialogues françois pour les jeunes enfans*, 43, 391–2, 394–6.
Plantin and Moretus, Antwerp (seventeenth century), printers, 402, 404.
Plato (*c* 429–347 B.C.), *and* form of the Earth, 504.
Platt, Sir Hugh (1552–1608), chemist, inventor of briquettes, &c., author of 'Newe and Admirable Arte of Setting of Corne', 80, 135, 679.
Plattes, Gabriel (*c* 1639), metallurgist, author of 'A Discovery of Subteraneall Treasure', 63, 681.
Pliny the Elder (23/4–79), Roman writer, *and* metallurgy, 40; *and* maps, 504; *and* wind-rose, 517; *and* chemistry, 677.
Plot, Robert (1640–96), antiquary, author of 'Natural History of Staffordshire', 34.
Plumier, C. (*c* 1701), author of *L'Art de tourner en perfection*, 336.
Plutarch (*c* 46–*c* 120), biographer, *and* Roman chronology, 578.
Polhem, Christopher (1661–1751), inventor, author of 'Political Testament' (1746), 19, 31, 342–4, 344 n, 455.
Ponte, Antonio da (*fl* end of sixteenth century), bridge designer, 424.
Porta, Giambaptista della (1536–1605), author of *Magiae naturalis*, 33–6, 40, 49, 53, 68, 231–2.
Power, Henry (1623–68), microscopist, 57.
Priestley, Joseph (1733–1804), chemist, 25.
Priscian (sixth century), poet, possibly author of *Carmen de ponderibus*, 67.
Proclus (fifth century), commentator on Ptolemy's *Almagest*, author of *Hypotyposis astronomicarum positionum*, 586, 588, 606.
Profatius (Jacob ben Tibbon, of Montpellier) (*c* 1288), astronomer, 599.
Ptolemy (Claudius Ptolemaeus of Alexandria) (*fl* 121–51), astronomer, 229–30, 409, 502–3, 508–11, 521–2, 530–9, 564–7, 583–4, 586–92, 599, 603, 605–6, 612–13, 615–16.
Ptolemy Euergetes (*c* 239 B.C.), Egyptian king, 564.
Pürbach, Georg (1423–61), astronomer *and* practical trigonometry, 608.
Pythagoras (*fl c* 531 B.C.), Greek philosopher, 504, 536, 626.

Quare, Daniel (*c* 1688), watch-maker, *and* repeating mechanism, 669–70.

Ralegh, Sir Walter (? 1552–1618), 2, 9 n 1, 481, 551.
Ramelli, Agostino (1531–90), mechanician, author of 'Le diverse et artificiose machine', 16, 18, 89–91, 96, 330–2, 337, 421–2.
Ramsden, Jesse (1735–1800), scientific instrument-maker, 555, 641–3.
Ratdolt, Erhard (1442–1528), of Venice, printer, 405.
Rathborne, Aaron (1572–1618), author of 'Surveyor', 541–3.
Ravenscroft, George (*fl* last part of seventeenth century), inventor of lead-crystal, 219, 221.
Réaumur, R. A. Ferchault de (1683–1757), chemist, 25, 28–9, 33, 49 n 1, 57, 689.
Règemortes, Jean Baptiste de (*fl c* 1720), canal-engineer, 464.
— Noël de (*c* 1726), canal-engineer, 464.
Regiomontanus (Johann Müller) (1436–76), astronomer, 532, 535, 547, 585, 591, 598, 617.
Reisch, Gregor (fifteenth to sixteenth century), rector of Freiburg University and author of *Margarita philosophica*, *and* survey instruments, 538.
Rembrandt (1607–69), artist, 407.
René II (last part of fifteenth century), Duke of Lorraine, 538.
Reuleaux, Franz (nineteenth century), author of 'The Kinematics of Machinery' (1876), 324 *and* n.
Rheita, Schyrlaeus de (*c* 1645), *and* telescope, 633.
Rhijnsburch, Jan van (*c* 1413), canal-engineer, 442.
Rhoissy, Marquis de (*fl* early seventeenth century), *and* canals, 461–2.
Riccobaldi of Ferrara (*c* 1474), chronicler, *and* printing output, 382.
Richard of Wallingford (? 1292–1335), astronomer and maker of astronomical instruments, 585, 593, 617.
Richelieu, Armand du Plessis de (1585–1642), Cardinal, French statesman, *and* town-planning, 291.

Ridley, Mark (*fl* last part of sixteenth and early seventeenth century), *and* field-survey instruments, 543.
Riefler, S. (b 1847), clock-maker, 671.
Rinaldi, Georges (*c* 1569), canal-engineer, 453.
Ringman (end of fifteenth and early sixteenth century), cartographer, 538.
Riquet, Pierre-Paul (1604–80), canal-engineer, 464–8.
— Jean-Mathias, son of Pierre-Paul, canal-engineer, 466.
Robert, Nicholas-Louis (1761–1828), inventor of a paper-making machine, 415.
Robertson, J. Drummond, author of 'The Evolution of Clockwork' (1931), 663 n 2.
Robins, Benjamin (1707–51), author of 'New Principles of Gunnery', 360.
Robinson, Thomas (*c* 1732), canal-engineer, 458.
Roderick, Bishop (*c* 1471), *and* pewter, 43.
Roemer [Römer], Ole (1644–1710), astronomer, *and* pendulum, 345; *and* surveying instruments, 543.
Rogers, Woodes (*c* 1710), privateer, 499.
Rolfe, John (1585–1622), English settler in Virginia, 9.
Römer, *see* Roemer.
Romulus, traditional founder of Rome, *and* calendar, 575.
Rosetti, G. V. (*c* 1540), author of *Plictho dell' arte de' Tentori*, 679.
Rovenzon, John (*c* 1613), metallurgist, 79, 80, 83.
Roy, P. Le, *see* Leroy.
Roy, William (1726–90), cartographer, 554.
Rudolph II (1576–1612), Emperor, *and* scientific instruments, 621.
Rupert, Prince (1619–82), nephew of King Charles I of England, *and* lead shot, 45; *and* iron ordnance, 367; *and* mezzotinting, 407.
Ruysch, J. (*c* 1508), cartographer, 535.

Sachs, Hans (1494–1578), poet, 40, 43.
Sacrobosco (thirteenth century), author of *Sphaera*, text-book of elementary astronomy, 547, 613.
Saint-Rémy, P. Surirey de (*c* 1650–1716), author of *Mémoires d'Artillerie*, 34, 38, 361, 369.
Sanctorius (1561–1636), physician, *and* diet, 24.
Sandrart (*c* 1675), writer on glass-engravers, 222, 224.
Sandys, William (*fl* 1636–62), canal-engineer, 458.
Sangallo (fifteenth century), architect, 288.
Savery, Thomas (? 1650–1713), *and* water-raising machine, 687.
Savorgnan, Giulio (*c* 1593), town designer, 286.
Savot, L. (*c* 1627), metallurgist, 37, 57.
Scaliger, Julius Caesar (1484–1558), scholar, *and* Julian Period, 581.
Scamozzi, Vincenzo (1552–1616), architect, 286.
Scanlon, Jessie, *and* lace-knitting, 186.
Scheele, Karl Wilhelm (1742–86), chemist, 25.
Scheiner, Christopher (1575–1650), *and* microscope, 632.
Schindler, C. C. (*c* 1687), assayer, 63.
Schlüter (*c* 1738), metallurgist, 28.
Schmidts, Michael (*c* 1660), canal-engineer, 454.
Schoch, C., author of *Die Länge der Sothisperioden beträgt 1456 Jahre* (Berlin-Steglitz, 1928), 563.
Schoeffer, Peter (? 1425–1502), printer, 377, 383–4, 386, 393.
Schoonbeke, Gilbert van (*c* 1552), canal-engineer, 453.
Schopper, Hartman (*c* 1568), author of *De omnibus illiberalibus sive mechanicis artibus humani ingenii*, 336, 391.
Schott, Gaspar (1608–66), *and* vacuum pump, 637.
Schreittmann, C. (*c* 1578), assayer, 60–1.
Schroeder, Johann (*c* 1641), chemist, 29.
Schürer, Christoph, of Saxony (seventeenth century), glass-blower, 678.
Schwab, Anton von (*c* 1742), chemist, 30.
— Max (*fl* middle of sixteenth century), goldsmith, 341.
'Schwarz, Berthold', mythical inventor of gunpowder, 366.
Seneca (d A.D. 65), Roman writer, *and* maps, 504.
Serlio, Sebastiano (1475–1554), architect, 257, 429.
Serres, Olivier de (1539–1619), French writer on agriculture, 13.
Seusenhofer, Conrad (late fifteenth–early sixteenth century) armourer to Emperor Maximilian I, 352–3.
Severus Sēbōkht (d 667), author of treatise on the astrolabe, 521, 606, 608.
Sforza, Ludovico (1479–99), ruler of Milan, *and* town-planning, 286.
Shish (*c* 1668), ship's carpenter, referred to by John Evelyn, 491.
Short, James (1710–68), instrument-maker, 233, 237.
Shortt (*c* 1920), clock-maker, 671.
Siegen, Ludwig von (1609–?), inventor of mezzotint process, 407.

Simon, Thomas (*c* 1651), coin engraver, 341.
Sinclair, Sir John (1754–1835), President of Board of Agriculture, sheep-breeder, 15, 135.
Siviard, St (d 687), shroud of, 198.
Sixtus IV (1471–84), Pope, *and* town-planning, 288.
Sixtus V (1585–90), Pope, *and* land drainage, 311–12; *and* town-planning, 289.
Smeaton, John (1724–92), engineer, 100, 102–4, 305, 436, 647.
Smith, Adam (1723–90), economist, 87.
Snell, Willibrord (1591–1626), cartographer and surveyor, 544.
Solon (*c* 594 B.C.), Greek statesman, *and* Greek calendar, 570.
Somerset, Edward, second Marquis of Worcester (1601–67), *and* new inventions and processes, 680.
Somerville, Lord (1765–1819), agriculturist, 15.
Sosigenes of Alexandria (*c* 47 B.C.), astronomer, *and* reform of Roman calendar, 576–7.
Spalding, James (*c* 1728), mechanician, 157.
Spallanzani, Lazaro (1729–99), scientist, *and* digestion of food, 25.
Spert, Thomas, captain of the *Henry Grâce à Dieu*, *temp.* Henry VIII, 487.
Spiers, of Ayr (nineteenth century), tool-maker, 111.
Sprat, Thomas (1635–1713), author of 'History of the Royal Society', 682–3.
Steers, Thomas (1672–1750), canal-engineer, 455, 458.
Stein, Sir Aurel (1862–1943), *and* silk, 202.
Stell, Joseph (*c* 1745), collaborator with John Kay, 168.
Stella, Tilemann (1524–89), canal-engineer, 450.
Stelluti, Francesco (1577–1653), *and* microscope, 632.
Stevin, Simon (1548–1620), mathematician, metrologist, hydraulic engineer, 61, 303–5, 307, 313, 371, 452, 542.
— Hendrik (1613–70), son of the above, 304.
Stevins (*c* 1777), Scottish scientist, *and* digestion of food, 25.
Stillman, J. M., author of 'The Story of Early Chemistry' (1924), 676.
Stoeffler (*c* 1512), author of *De usu astrolabii*, 536.
Strabo (? 63 B.C.–? A.D. 24), Greek geographer, *and* terrestrial globe, 614.
Stradanus [Van der Straat, Jan] (1536–1604), artist, 350–1, 394–5, 397–9, 707.
Sturtevant, Simon (*c* 1612), metallurgist, 79, 83.
Suetonius (*c* A.D. 121), Roman biographer, *and* maps, 504.
Sully, Maximilian de Rosny, Duke of (*fl* 1589–1610), Minister of Henry IV of France, *and* canals, 459–61; *and* horology, 557; *and* town-planning, 291.
Sutton, Henry (d 1665), scientific instrument-maker, 623.
Swedenborg, Emanuel (1688–1772), Swedish philosopher, 31, 51.
Sylvester II (999–1003), Pope, *see* Gerbert.
Synesius (*c* A.D. 410), writer of letter concerning astrolabe, 603, 606.

Tachenius, Otto (*c* 1620–1700), German chemist settled at Venice, author of *Hippocrates chimicus*, 681, 704.
Tartaglia, Niccolò (1500–57), mathematician, author of *Quesiti e inventioni*, *and* artillery, 374, *and* survey-instruments, 539.
Taylor, James, of Lancashire (*c* 1754), mechanician, 162.
Telford, Thomas (1757–1834), engineer, 428, 455.
Theodosius (378–95), Roman emperor, *and* Olympiads, 572.
Theon, of Alexandria (*c* A.D. 375), commentator on Ptolemy's *Almagest*, 586–8, 591, 606.
Theophilus Presbyter (tenth century), metallurgist, 34, 48–9, 206–8, 364, 677.
Theophrastus (*c* 372–287 B.C.), Greek writer, *and* building construction, 250.
Thevet, André (1502–90), traveller, introducer of tobacco seeds in France, 8.
Thiout (*c* 1741), mechanician, 345.
Thölde, Johann, *see* 'Basil Valentine'.
Thompson, R. Campbell, author of 'A Dictionary of Assyrian Chemistry and Geology' (1936), 224 n.
Ticquet (eighteenth century), *and* French coal industry, 86.
Tilly, Johann Tzerclaes, Count (d 1632), military commander, *and* cannon-balls, 31.
Titus (79–81), Roman emperor, *and* destruction of Jerusalem, 574.
Tompion, Thomas (1639–1713), clock-maker, 557, 665, 667.
Torricelli, Evangelista (1608–47), pupil of Galileo, 234, 332, 636.
Tourville, A. H. de C. de (1642–1701), *and* approval of English shipbuilding methods, 492.
Townshend, Charles, Viscount (1674–1738), *and* agriculture, 15.
Trajan (98–117), Roman emperor, founder of Timgad, Algeria, 280.
Trechsler, Christopher (*fl* 1571–1624), Dresden instrument-maker, 629.
Trew, John (*c* 1564–7), canal-engineer, 451.
Truchet, Sébastien (1657–1729), canal-engineer, 46.
Tull, Jethro (1674–1741), agriculturist, 15.

Turriano (sixteenth century), watch-maker to Emperor Charles V, 16.

Tusser, Thomas (? 1524–80), author of 'Five Hundreth Good pointes of Husbandry', 134.

Ulugh Beg (1394–1449), Persian ruler, *and* observatory at Samarkand, 584.

Urban VIII (1623–44), Pope, *and* land drainage, 312, 314.

Valdés, Diego Flores de (sixteenth century), commander of part of Spanish Armada 1588, 480.

Vallans, William (*fl* 1578–90), author of 'Tale of Two Swannes', quoted concerning lock mitre-gates, 451–2.

Van der Heyden (*c* 1620), dyer, 695.

Van der Straat, *see* Stradanus.

Van Helmont, Johann Baptista (? 1577–1644), scientist, *and* dietetics, 24.

Van Linschoten (seventeenth century), Dutch traveller, *and* Indian lacquering.

Van Robais (seventeenth century), manager of model textile factory at Abbeville, France, 152.

Varro, Marcus Terentius (116–27 B.C.), Roman grammarian, *and* maps, 504; *and* Roman chronology, 578.

Vauban, Sébastien le Prestre de (1633–1707), military engineer, 372–3, 467.

Vaucanson, Jacques de (1709–82), French mechanician, 166, 169.

Verantius (*c* 1595), Venetian mechanician, author of *Machinae novae*, 18.

Vergil, Polydore (d 1555), scholar, *and* invention of printing, 381.

Vermuyden, Sir Cornelis (?1590–1677), hydraulic engineer, author of 'Discourse touching the Drayning the Great Fennes' (1642), 316, 318, 320–1.

Verovio, Simone (*c* 1586), of Rome, publisher of early music book, 409.

Vierlingh, Andries (1507–79), author of *Tractaet van dyckagie*, 301–2, 305, 452.

Vignola, Giacomo da (1507–73), canal-engineer, 450.

Visscher, Anna Roemers (1584–1651), Dutch poetess and glass-engraver, 229.

Vitruvius (first century B.C.), Roman architect, author of *Architectura*, 245, 247–8, 250, 253, 265, 276, 504, 511–13, 543, 601–2, 604–5, 628.

Viviani, Vincenzio (1621–1703), pupil of Galileo, and a founder of *Accadèmia del Cimento*, 232, 315.

Vizinho, José (fifteenth to sixteenth century), astronomer and mathematician, 547.

Voltaire, François-Marie Arouet de (1694–1778), *and* canals, 466.

Vroom, Hendrik Cornelisz (1566–1640), artist, 486, plate 22.

Waldseemüller, Martin [Hylacomylus] (*c* 1470–*c* 1518), author of *Cosmographiae Introductio*, 535 *and* n, 536, 538.

Wallis, John (1616–1703), mathematician, 257.

Walsingham, Sir Francis (? 1530–90), Secretary of State, *and* land drainage, 317.

Wang Ching (*c* 70), Chinese canal-engineer, 439.

Warwick, Earl of (1381–1439), drawings illustrating life of, *and* ships, 475.

Watt, James (1736–1819), engineer, 84, 368, 647.

Weale, Samuel (*c* 1692), mechanician, 157.

Weigel, von (*c* 1773), 11–12.

Werner, Johann (*c* 1514), cartographer, 535–6.

Weston, Sir Richard (1591–1652), canal-engineer, 457.

Wilkinson, John (1729–1808), ironmaster, 367.

William III (1689–1702), English king, *and* window sashes, 267.

William IV (*c* 1561), Landgrave of Hesse, *and* clocks, 658.

William (*c* 1631), Landgrave of Hesse, *and* rifles, 358.

Williams, Thomas (eighteenth century), *and* building of the Pont-y-ty-Prydd, 435.

Willibrord, St (? 657–? 738), Archbishop of Utrecht, vestments of, 197.

Winchcombe, John (d 1520), clothier, 151.

Windsor, Herbert, Lord (eighteenth century), *and* industrialization of Glamorgan, 434.

Winthrop, John (1606–76) *and* distillation of wood, 685.

Witsen, Nicolaas (1641–1717), burgomaster of Amsterdam, *and* coffee, 6.

Witt, Nicolaas Corneliszoon de, of Alkmaar (*c* 1623), hydraulic engineer, 312.

Wolff, D., of The Hague, glass-engraver, 229.

Wolsey, Thomas (1475–1530), Cardinal and Archbishop of York, *and* Renaissance architecture, 245.

Wratten (nineteenth century), Sussex cooper, 129.

Wren, Sir Christopher (1632–1723), architect, 246, 252, 254–60, 262, 265–7, 297–8.

Wright, Edward (*c* 1558–1615), mathematician, author of 'Certain Errors in Navigation', 464, 543, 551.

Wyatt, John (1700–66), mechanician, 162.

Wynn Timmins & Co., Birmingham, *and* catalogue of tools (*c* 1892), 116.

Yarranton, Andrew (1616–84), canal-engineer, 458.
Yarwell, John (1648–1712), optical instrument-maker, 634.
Young, Arthur (1741–1820), agriculturist, 15.

Zacuto, Abraham (1450–? 1515), astronomer and mathematician, 547.
Zeller, Anton, of Aschhausen (*c* 1608), metallurgist, 32–3.
Zimmerman, Samuel (*c* 1573), assayer, 64.
Zonca, Vittorio (1568–1602), architect-engineer of Padua, author of *Novo Teatro di Machine et Edificii, and* canals, 441 n 2, 451 *and* n; *and* coinage machinery, 342; *and* metallurgy, 41; *and* textile machinery, 172.

II. INDEX OF PLACE-NAMES

Aa, river, Flanders, 453.
Aachen (Aix-la-Chapelle), Germany, 72, 196.
Abbeville, Picardy, France, 152, 703.
Abbiate, near Milan, Italy, 444, 446.
Abingdon, Berkshire, 456.
Abyssinia, 530.
Acre, Palestine, 159.
Adda, river, Italy, 446, 448–9.
Aden, 5, 106.
Adige, river, Italy, 309.
Adriatic, sea, 525.
Africa, 159, 356, 477, 518–19, 530, 544.
— north, 183, 514, 523.
Aire, river, Yorkshire, 458.
Akeman Street, England, 278.
Albania, 579.
Aleppo, Syria, 600.
Alexandria, Egypt, 22, 210, 275, 473, 504–6, 531, 587, 605.
Alkmaar, Holland, 312, 679.
Allier, river, France, 463.
Alps, mountains, 308, 417.
Altare, near Genoa, 217.
Alton, Hampshire, 116.
Alzau, stream, Languedoc canal, 464, 467.
Ambleside, Westmorland, 277.
Amiens, France, 544, 703.
Amoy, Fukien, China, 696.
Amstel, river, Holland, 293–5.
Amsterdam, Holland, 6, 89, 293–5, 305, 312, 402, 485, 695, 700.
Amwell, Hertfordshire, 543.
Anatolia (Asia Minor), 695.
Ancona, Italy, 311.
Andalusia, Spain, 152.
Andernach, Germany, 16.
Antikythera, island between Greece and Crete, 617–18.
Antinoë (Antinoöpolis), Egypt, 195.
Antioch, Syria, 275, 282.
Antrim, Ireland, 162.
Antwerp, Belgium, 159, 391, 401–2, 452, 713.
Aosta, Italy, 280.
Aquileia, Italy, 286.
Arboga, river, Sweden, 455.
Arctic Circle, 506, 509, 553.
Arcueil, near Paris, France, 462.
Arno, river, Italy, 309–10, 428, 448.
— valley of the, 218.
Aryn, imaginary place on the equator, 521.
Asia, 159, 164, 378, 380, 518–19.
Assur, Mesopotamia, 271.
Aswan, on R. Nile, 506, *see also* Syene.
Athens, 272–3, 281, 568, 572, 618.
Atlantic Ocean, 459–60, 472, 474, 476–7, 522, 525.
Aude, river, France, 459, 465.
Augsburg, Bavaria, 341, 380–1, 406, 535, 585, 621–2.
Auron, river, France, 450.
Austria, 161, 341, 407.
Autun, France, 504.
Auxerre, France, 504.
Avignon, France, 287, 418.
Avon, Somerset, river, England, 457.
Avon, Warwick, river, England, 457.
Azores, islands, 531, 544, 549.

Babylon, 270–1, 559, 566, 568, 571, 574.
Baghdad, Mesopotamia, 521, 529, 584.
Balkans, the, 8.
Baltic, islands of the, 89.
— Sea, 444, 455, 499, 532.
Baluchistan, south-west Asia, 505.
Bamberg, Bavaria, 405.
Basel, Switzerland, 168, 538.
Basque country, 186.
Bassa Valle Padana, 309.
Bath, Somerset, 152, 260, 277, 457.
Bayonne, France, 476.
Beauvais, France, 241.
Bedford Level, *see* Great Level.
Beemster, meer, Holland, 306, 321.
Belgrade, Yugoslavia, 279.
Bengal, India, 159.
Bereguardo, near Pavia, Italy, 446.
Bergen, Norway, 533.
Bergen-op-Zoom, Holland, 316, 318.
Bergerac, France, 16.
Bergermeer, the, Holland, 302.

Berlin, Germany, 450, 454, 682.
Berri, France, 152.
Berwick-on-Tweed, Northumberland, 284.
Béziers, Hérault, France, 467.
Bidford-on-Avon, Warwick, 457.
Bideford, Devonshire, 418.
Binasco, Lombardy, 446.
Birka, Sweden, 202.
Birmingham, England, 162.
Bisenzio, river, Italy, 314–15.
Black Sea, 523.
Blackfriars, London, 586.
Blaencorrwg, Glamorganshire, 140.
Blenheim, Bavaria, 347.
Blois, France, 254.
Boesinghe, near Brussels, 454.
Bohemia, 82, 206, 220–1, 229, 689.
Bolivia, 1.
Bologna, Italy, 312, 314, 409, 447, 450, 504.
Bordeaux, France, 318, 493.
Boscoreale, near Pompeii, Italy, 613.
Boston, Lincolnshire, 515.
Bothnia, Gulf of, Baltic, 533.
Bourges, Cher, France, 291, 450.
Bow, Essex, 695.
Brabant, Low Countries, 301–3, 320.
Brandenburg, Prussia, 449–50.
Brandon, Norfolk, 356.
Brazil, 4, 6, 484.
Brenta, river, Italy, 441 n 2, 447, 451.
Breteau, near Briare, France, 460.
Briare, on R. Loire, France, 460.
Brieskow on the Oder, Germany, 454.
Bristol, England, 226, 457, 688, 703.
Brittany, France, 89, 95, 96, 97, 99, 102, 104, 478.
— harbours of, 525.
Broseley, Shropshire, 80, 84, 688.
Bruges, Flanders, 303, 453, 473.
Brunswick, Germany, 160.
Brussels, Belgium, 380, 450–3.
Bulgaria, 579.
Burford, Oxfordshire, 152.
Burgos, Spain, 201.
Bury, Lancashire, 169.
Byzantium, 279, *and see* Constantinople.

Cadiz, Spain, 477.
Caernarvon, Wales, 284.
Caerwent, Monmouthshire, 277.
Cairo, Egypt, 179, 182, 269, 584, 613.
Calais, France, 74.
Calder, river, Yorkshire, 458.
Calicut, India, 178.
Cambrai, France, 178.
Cambridge, England, 103, 241–2.
Cambridgeshire, England, 152, 315.
Cammazes, near Castelnaudary, France, 467.
Canary Islands, 6, 90, 477, 531, 544, 694.
Canopus, Egypt, 564.
Canterbury, Kent, 196, 241, 277, 596–7.
Canton, China, 696.
Carambuc (Peking), 380.
Carcassonne, France, 241, 283, 369, 459, 465.
Caspian Gates, 505.
Casquets, rocks, Channel Islands, 499.
Cassel, Germany, 343, 658.
Castelnaudary, Aude, France, 464.
Castile, Spain, 152, 170, 480, 703.
Cesse, river, Languedoc, France, 466–7.
Châlons-sur-Marne, France, 179, 290, 441.
Ch'ang-au, China, 439.
Charleville, Ardennes, France, 290.
Chartres, France, 241.
Châtellerault, Vienne, France, 430–1.
Chaumont-en-Vexin, Oise, France, 319.
Chemnitz, Saxony, 28.
Chepstow, Monmouthshire, 458.
Cher, river, France, 450.
Chesnoy, near Montargis, France, 462.
Chester, England, 277–8.
Chiangsu, province, China, 439.
Chiaravalle, Italy, 309.
Chichester, Sussex, 265, 267, 278.
Chiddingfold, Surrey, 207.
Chilterns, the, England, 146.
Chinese Turkestan, 195, 201–2.
Cirencester, Gloucestershire, 152, 277.
Civita Lavinia, Italy, 596.
Civita Vecchia, Italy, 311.
Coblenz, Germany, 284.
Colchester, Essex, 277–8.
Cologne, Germany, 196, 279, 284.
Commachio, Italy, 314.
Como, Lake, Italy, 448.
Constance, Baden, 386, 389.
— Lake, 427.
Constantinople, 196, 279, 361, 363, 405.
Conway, Wales, 284.
Corinth, Greece, 275.
Cornwall, England, 140–1, 144, 152, 261, 689.
Cotswolds, the, England, 145, 147, 257, 260–1.
Courpalet, Rigole de, Orleans canal, 463–4.
Coventry, Warwickshire, 703.
Cranbrook, Kent, 95.
Cuba, 3, 8.
Cues, Rhineland, 585.
Cumberland, England, 63, 140, 152.
Cyprus, 6, 159.

Dagenham, Essex, 422.
Dalmatian coast, Adriatic, 514.
Damascus, Syria, 115, 159, 275, 350.
Dammarie, near Montargis, France, 462.
Damme, near Bruges, Flanders, 442.
Danzig, 167.
Daoulas, Brittany, 178.
Dartmouth, Devonshire, 481, 487.

Dean, Forest of, Gloucestershire, 31, 78.
Delfshaven, Holland, 442.
Delft, Holland, 304.
Delos, Greece, 274.
Delvenau, river, Germany, 444.
Denmark, 97, 99, 217, 579.
Deptford, London, 485, 491.
Derbyshire, England, 80, 260.
Dergmeer, the, Holland, 302.
Devon, England, 140–1, 146, 152, 261.
Dieps- and Tjaalingermeer, the, Holland, 302.
Dijon, France, 379.
Don, river, Yorkshire, 458.
Donegal, Ireland, 162.
Dorchester, Oxfordshire, 241.
Dorset, England, 152, 260.
Dover, Kent, 278, 317, 459, 651.
Dresden, Germany, 629.
Dublin, Ireland, 455.
Dudley, Worcestershire, 226.
Dundee, Scotland, 176.
Dunkirk, France, 453.
Dura Europus, Mesopotamia, 275.
Durham, England, 196–7.

East Anglia, England, 98, 101, 103, 107, 140, 145, 261.
East Indies, 4, 6, 228, 525, 679, 690.
Edinburgh, Scotland, 176, 361.
Egmondermeer, the, Holland, 302.
El Mina, West Africa, 547.
Elbe, river, Germany, 444, 455.
English Channel, 525.
Ephesus, Asia Minor, 275, 282.
Ermine Street, England, 278.
Erzgebirge, the, Bohemia and Saxony, 28.
Eskilstuna, river, Sweden, 452, 455.
Essex, England, 143, 152, 265, 487.
Estremadura, Spain, 152.
Ethiopia, 5, 505, 522.
Euphrates, river, 270, 438.
Évreux, France, 241.
Exe, river, England, 451.
Exeter, Devonshire, 277, 451, 456.

Fabriano, near Ancona, Italy, 415.
Faenza, Italy, 678.
Fairford, Gloucestershire, 242.
Falun, Sweden, 342.
Fayum, the, Egypt, 512.
Fens, the, England, 315–22, 459.
Ferrara, Italy, 312, 314, 382, 678.
Ferro, Canary Islands, 531.
Ferté-sous-Jouarre, La, France, 16.
Finisterre, Cape, Spain, 548.
Finland, 553.
Finow, river, Germany, 454.
Fintelle, Flanders, 441 n 2.
Fiume Morto, Italy, 314.
Flint, Wales, 284.
Florence, Italy, 230, 245–50, 254, 258, 280, 309–10, 406, 418, 424, 428–30, 448, 694, 707.
Flushing, Holland, 486.
Fortunate Islands, *see* Canary Islands.
Fostat *or* Fustat (old Cairo), 179, 182.
Frankfurt on the Oder, Prussia, 454.
Freiburg, Baden, 538.
Fresquel, river, near Castelnaudary, France, 464–5.
Friesland, west Holland, 301, 305.
Friston, Suffolk, 94.
Fusina, Italy, 441, 442.

Ganges, river, India, 506.
Garonne, river, France, 459, 466.
Gascony, France, 283.
Gaul, 206, 509.
Gazonne, Étang de la, near river Trezée, France, 462.
Gebel el-Arak, Egypt, 110.
Gedding, Suffolk, 101.
Genoa, Italy, 170, 217, 248, 478, 703; Genoese colonies in East, 380.
Gibraltar, 505, 523.
Gihon, near Jerusalem, 510.
Glamorganshire, Wales, 139, 146–7, 434.
Glasgow, Scotland, 705.
Gloucester, England, 172, 241, 277, 688.
Gloucestershire, England, 9, 137, 152.
Golden Horn, Constantinople, 433.
Goslar, near Halberstadt, Germany, 691–2, 706.
Göta, river, Sweden, 455.
Göteborg, Sweden, 455.
Gouda, Holland, 442.
Governolo, on river Mincio, Italy, 442.
Graff-Hendriks polder, Steenbergen, Brabant, 301.
Gravelines, France, 453.
Great Level *or* Bedford Level, England, 316–21.
Greenland, 532–3, 705.
Greenwich, London, 497, 521, 665.
Groningen, Holland, 303.
Grote Wiericke channel, Holland, 304.
Guildford, Surrey, 456–7.
Guinea, West Africa, 547, 680.

Haarlem, Holland, 175, 377, 383, 392.
Haarlemmermeer, Holland, 307.
Hague, The, Holland, 229, 663.
Hailsham, Sussex, 129.
Halifax, Yorkshire, 152.
Hall, Tyrol, 216, 341.
Hamburg, Germany, 225.
Hampshire, England, 139, 152.
Harappa, Indus valley, 270.

Harz Mountains, Germany, 82.
Hatfield Chase, Yorkshire, 320.
Havel, river, Prussia, 450–1, 454–5.
Haverhill, Suffolk, 101.
Heckington, Lincolnshire, 96.
Henrichemont, Cher, France, 290–1.
Herculaneum, near Naples, Italy, 237, 596.
Herefordshire, England, 152.
Hermus, river, Asia Minor, 704.
Hertfordshire, England, 152, 265.
Het Gein, Holland, 441.
Hindu-Kush, mountains, central Asia, 505.
Hjälmar, Lake, Sweden, 452, 455.
Holy Land, the, 473.
Honan, province, China, 439.
Hounslow Heath, Middlesex, 554.
Huai, river, China, 439.
Huaian, China, 440.
Huang-Ho, river, China, 438.
Humbeek, Flanders, 453.
Humber, the, England, 260.
Hungary, 82, 579, 706.
Huntingdonshire, England, 315.

Iberian peninsula, 95, 100.
Iceland, 532.
Iffley, Oxfordshire, 456.
Ij (*or* Y), river, Holland, 293–4.
Indian Ocean, 521.
Indus, river, 438, 505.
Irwell, river, England, 458.
Isle of Man, 140.
Islington, London, 543.

Japan, 5, 378, 524, 579, 696–7.
Jarrow, Durham, 595.
Jerash, Palestine, 280.
Jerusalem, 159, 520, 573–4.
— Pool of Siloam, 510.
Joachimsthal, Bohemia, 28.
Jordan, Palestine, 280.

Kahun, Egypt, 269.
Kaifeng, China, 439.
Karnak, Egypt, 601.
Kendal, Westmorland, 152.
Kennet, river, England, 457.
Kent, England, 101, 152, 261, 265, 487, 694.
Kerch, Crimea, 200.
Kerkmeer, the, Holland, 302.
Khurasan, Persia, 191.
Kingston-upon-Hull, Yorkshire, 284.
Kittis, Finland, 553.
Korea, 378.
Kromwater, the, Holland, 302.
Kuangsi, province, China, 439.

Lake District, the, England, 261.
Lambeth, London, 238.
Lambro, river, Italy, 446.
Lampy, stream, Languedoc Canal, 464, 468.
Lancashire, England, 89, 159, 162, 260, 264.
Landes, France, 183.
Languedoc, France, 15, 152, 283, 319, 459, 464–8.
La Rochelle, Bay of Biscay, France, 679.
Laudot, river, near Toulouse, France, 468.
Lauenburg, Germany, 443.
Lavenham, Suffolk, 152.
Lea, river, England, 451, 456.
Leeds, Yorkshire, 257, 458.
Leghorn (Livorno), Italy, 287.
Leicestershire, England, 152.
Leiden, Holland, 167, 303, 452, 663, 695.
Lek, river, Holland, 442.
Leominster, Herefordshire, 154.
Lepanto, Gulf of Corinth, 350, 473.
Lepini, mountains, Italy, 311.
Lers, river, near Toulouse, France, 464–5.
Lesparre, Gironde, France, 319.
Levant, the, 159, 217, 472, 702.
Liége, Belgium, 72, 74–5, 118.
Liepe, on tributary of Oder, Germany, 454–5.
Liguria, Italy, 218.
Lilla Edet, Sweden, 455.
Lille, France, 453.
Limmat, river, Switzerland, 428.
Limoges, France, 241.
Lincoln, England, 241, 277.
Lincolnshire, England, 101, 146, 152, 315–16.
Lisbon, Portugal, 480, 544, 549.
Liverpool, Lancashire, 458.
Livoli, river, Italy, 311.
Lixhe, near Liége, Belgium, 586.
Llanbrynmair, Montgomeryshire, 141.
Loing, river, France, 460, 462–4.
Loire, river, France, 459–60, 462–4, 543.
— valley, 95.
Lombardy, Italy, 439, 444–6, 449.
London, 5–6, 11, 77, 80, 116, 145, 167, 203, 221–2, 234, 245, 252, 254, 256–9, 264, 283–4, 295–9, 340, 416, 418, 531, 543–4, 553, 621, 663, 667, 671, 679, 681, 702–3.
— New River, 464, 543.
— Roman, 277–9.
— *See also in Index of Subjects.*
Long Island, U.S.A., 89.
Lorraine, France, 237, 240.
Louvain, Brabant, 539, 586, 621.
Loyang, China, 439.
Lübeck, Germany, 444.
Lucca, Italy, 199, 280.
Lund, Sweden, 533.
Lyons, France, 165, 189, 191, 396 n.
Lys, river, France and Belgium, 453.

Maastricht, Holland, 196, 202.
Mable, river, France, 291–2.

Madeira Islands, Atlantic Ocean, 6, 544.
Madrid, Spain, 341.
Magdeburg, Saxony, 31.
Maggiore, Lake, Italy, 444.
Maidenhead, Berkshire, 441.
Maidstone, Kent, 702.
Mainz, Germany, 377, 381–5, 388–90, 393, 404.
Majorca, Balearic Islands, 544.
Mälar, Lake, Sweden, 452, 455.
Malmesbury, Wiltshire, 152.
Malpas tunnel, Languedoc canal, France, 467.
Malplaquet, Belgium, 350.
Malvoisine, France, 544.
Manchester, Lancashire, 152, 168.
Marāgha, Persia, 584.
Mareotis, Lake, Egypt, 275.
Margate, Kent, 100.
Marlborough, Wiltshire, 504.
Marlow, Buckinghamshire, 441.
Marne, river, France, 441.
Marseilles, France, 703.
Marzabotto, Italy, 276.
Mecca, Arabia, 580, 599–600.
Mecklenburg, Germany, 285, 450.
Medina, Arabia, 580.
Mediterranean region, 95, 96 n, 100, 103, 159, 240, 271–2, 465, 530, 683.
— Sea, 459–60, 466–7, 471–4, 476–7, 479–80, 493, 509, 518–19, 522–3, 525, 544, 548.
Mendip Hills, Somerset, 703.
Merionethshire, Wales, 140.
Meroë, R. Nile, 509.
Mersey, river, England, 458.
Mesopotamia, 270–1, 502, 521.
Meuse, river, France and Low Countries, 74.
Mexico, 1, 3, 73, 695.
Middelburg, Zeeland, 301.
Middlesex, England, 265.
Milan, Italy, 39, 196, 202, 285–6, 309, 444, 446–50, 459, 656.
— San Marco lock, 446–8.
Miletos, Asia Minor, 272–3.
Modena, Italy, 230, 504.
Mohenjo-Daro, Indus valley, 270.
Molgora, river, Italy, 446.
Mölln, Lake, Germany, 444.
Mongolia, southern, 195.
Monmouth, England, 458.
Monmouthshire, England, 697.
Monpazier, Dordogne, France, 282–3.
Mons, Belgium, 72.
Montagne Noire, near Carcassonne, France, 467.
— Rigole de la, near Carcassonne, France, 467–8.
Montargis, Loiret, France, 460, 462–4.
Monteverdi, Lombardy, 309.
Mont-Olympe, on river Meuse, France, 290.
Mosul, Mesopotamia, 179.
Munich, Bavaria, 598.
Murano, Venice, 209, 217–18, 678.

Nancy, Meurthe-et-Moselle, France, 290.
Nantes, France, 463.
Naples, Italy, 231, 612, 705.
Narbonne, Aude, France, 468.
Naurouze, near Toulouse, France, 465, 468.
Neagh, Lough, Northern Ireland, 455.
Nene, river, England, 316.
Neubrandenburg, Germany, 285.
Neuhaus on the Spree, Prussia, 454.
Newbury, Berkshire, 151–2, 457.
Newcastle-upon-Tyne, Northumberland, 77, 84.
Newfoundland, 705.
Newry, Northern Ireland, 455.
Nicea, Asia Minor, 579.
Nidrosia, Norway, 533.
Nieuport, Flanders, 442, 453.
Nile, river, 438–9, 502, 519, 521, 560–1.
Nineveh, Mesopotamia, 271.
Nivernais (Nièvre), France, 689.
Norfolk, England, 97, 152, 315–16.
Normandy, France, 238, 240, 319.
North Sea, 444, 455, 476.
Northampton, England, 162.
Northamptonshire, England, 137, 260.
Northumberland, England, 152.
Norway, 532, 683.
Norwich, Norfolk, 115.
Nun, Cape, Morocco, 544.
Nuremberg, Germany, 238, 337–8, 342, 358, 380–1, 532, 534–5, 548, 585, 621–2, 652, 656, 678.

Oder, river, Germany, 454.
Olynthos, Macedonia, 273–4.
Orbiel, river, Languedoc canal, France, 467.
Orleans, France, 225, 463.
Oslo, Norway, 533.
Ostend, Flanders, 453.
Ostia, Italy, 280–2.
Otranto, Italy, 474.
Otterspoor, Holland, 441.
Ouse, Fenland river, England, 316.
Ouse, river, Yorkshire, 458.
Oxford, England, 6, 241, 257, 265–6, 402, 441, 585–6, 681.
Oxfordshire, England, 147.

Paclais, Loire-Inférieure, France, 96.
Paderno, on river Adda, Italy, 448–50.
Padua, Italy, 249, 314, 447, 451 n, 677.
Palazzolo, Italy, 309.
Palermo, Sicily, 198.
Palestine, 573–4.
Palma Nuova, Venetia, 286.

Palmyra, Syria, 195, 275, 280, 521–2.
Paris, France, 5–6, 115, 178, 241, 252, 254–5, 258, 293, 333, 340–1, 345, 358, 397 n, 398, 423, 425, 430, 441, 463, 531, 554, 585, 616, 674, 696.
Parma, Italy, 446.
Passchendaele, Flanders, 453.
Pavia, Italy, 446, 449.
Peking, China, 440.
Pennines, the, England, 257, 260–1.
Pergamum, Asia Minor, 614.
Périgord, France, 34.
Persian Gulf, Arabian Sea, 505.
Peru, South America, 1, 3, 73, 182, 554.
Pesaro, Italy, 313.
Pewsey, vale of, Wiltshire, 147.
Philippines, the, 4, 8.
Picardy, France, 91, 175, 319.
Piedmont, Italy, 218.
Piperno, Italy, 311.
Piraeus, Greece, 271–2.
Pisa, Italy, 230, 314, 662.
Pitchford, near Wenlock, Shropshire, 688.
Plaine, Rigole de la, Languedoc canal, France, 468.
Plaue, lake, Germany, 455.
Po, river, Italy, 310, 314, 446.
Poitou, France, 319.
Poland, 229, 579.
Pompeii, Italy, 237, 274, 512.
Pont Crouzet, near Cammazes, France, 468.
Pontine Marshes, Roman Campagna, Italy, 311–13, plate 19.
Pontypool, Monmouthshire, 688–9.
Pontypridd, Wales, 434.
Portland, England, 260.
Portsmouth, Hampshire, 491.
Potsdam, Prussia, 225.
Prague, 223, 621, 658.
Priene, near Miletos, Asia Minor, 273–4.
Provence, France, 159, 319.
Purbeck, Dorset, 396.
Pyrenees, mountains, France and Spain, 596.

Quiberon Bay, Brittany, 499.

Rammelsberg, Germany, 692.
Rathenow, Prussia, 450.
Ravenna, Italy, 312.
Reading, Berkshire, 457.
Red Sea, 439.
Regensburg, Bavaria, 284.
Reno, river, Italy, 314.
Repudre, river, Languedoc canal, France, 467.
Revel, near Toulouse, France, 464.
Rhine, river, 237, 427–8.
Rhineland, the, 206, 537–9.
Rhodes, east Mediterranean, 505–6, 508–10, 564.
Richelieu, Indre-et-Loire, France, 290–2.
Rietgreb, the, Holland, 302.
Rimini, Italy, 311.
Rivenhall, Essex, England, 241.
Rogny, near Montargis, France, 460, 462–3.
Rome, Italy, 53, 209–10, 214, 220, 245–50, 253–5, 257–8, 266, 276, 279–82, 287–9, 312, 349, 409, 511–12, 534, 566, 575, 578, 657.
Rothenburg ob der Tauber, Bavaria, 284.
Rouen, France, 241, 653.
Rudge Coppice, near Marlborough, Wiltshire, 504.
Ruhr, the, Germany, 85.
Rupel, river, Flanders, 452–3.
Rutland, England, 260.
Rye, Sussex, 487.

Sahara, the, North Africa, 525, 544.
St Albans, Hertfordshire, 276.
St Andrews, Fife, Scotland, 667.
Saint-Dié, Vosges Mountains, 538.
St-Ferréol, Languedoc canal, France, 468.
St Gall, Switzerland, 594–5.
Saint-Gobain, France, 238.
St Gotthard Pass, Switzerland, 417.
St Michael Island, Azores, 531.
Saint-Moritz, Switzerland, 197.
Saintonge, France, 319.
St Privé, near Briare, France, 463.
— Rigole de, 464.
St Vincent, Cape, Portugal, 506.
Salisbury, Wiltshire, 241, 650.
Salisbury Plain, England, 147.
Salvatori, Lombardy, 309.
Salzburg, Austria, 605.
Samarkand, Turkestan, 584.
Samos, Greece, 511.
Sandford-on-Thames, near Oxford, 456.
Saône, river, France, 459.
Sarlièves, lake, Puy-de-Dôme, France, 319.
Savenay, Loire-Inférieure, France, 96.
Savona, Genoa, Italy, 703.
Saxony, 42, 82, 161, 342, 689, 703.
Scandinavia, 181, 532–3.
Scarpe, river, France, 441 n 1, 453.
Schaffhausen, Switzerland, 427–8.
Schelde, river, Flanders, 452.
Schiedam, Holland, 442.
Schneeberg, near Meissen, Saxony, 218, 703.
Segovia, Spain, 152, 341.
Seine, river, France, 237, 293, 333, 459–60, 464, 477, 543.
Selinus, Sicily, 273.
Senne, river, Flanders, 452.
Sens, Yonne, France, 195–6, 198, 202.
Serchio, river, Italy, 314.
Sète, near mouth of R. Aude, France, 465, 467.
Severn, river, England, 84, 457, 688.

Seveso, river, Italy, 444.
Seville, Spain, 703.
Sèvres, near Paris, France, 679.
Sezze, Italy, 311.
Shantung, province, China, 440.
Sheffield, Yorkshire, 113, 115, 458.
Shetland Islands, Scotland, 186.
Shrewsbury, Shropshire, 457.
Shropshire, England, 31.
Siam, 159.
Sicily, 521, 525.
Siegen, Germany, 32.
Siena, Italy, 678.
Siestan, Persia, 106.
Silchester, Hampshire, 111, 277–8.
Silesia, Germany, 151.
Skermer, the, Holland, 321.
Smyrna, Asia Minor, 159, 704.
Sofala, south-east coast of Africa, 521.
Solingen, Germany, 115.
Somali coast, East Africa, 506.
Somerset, England, 152.
Sonderak, Holland, 304.
Sor, river, near Toulouse, France, 464–5, 467–8.
South Carolina, 5.
Southampton, Hampshire, 283, 473–4, 487.
— Water, 476.
Spaarndam, Holland, 442, 450, 452.
Sparta, Greece, 273.
Spree, river, Prussia, 450, 454.
Staffordshire, England, 84.
Stane Street, England, 278.
Stavanger, Norway, 533.
Stecknitz, river, Germany, 443–4.
Steenbergen, Brabant, 301, 320.
Stjärnsund, Sweden, 342.
Stockholm, 224, 455, 533, 682.
Stour, river, Worcestershire, 458.
Stourbridge, Worcestershire, 458.
Stra, near Padua, Italy, 447, 451 n.
Strasbourg, France, 383–4, 537–8, 655.
Stratford, Essex, 695.
Stratford-on-Avon, Warwickshire, 458.
Styria, Austria, 115.
Sudan, Africa, 521.
Sudbury, Suffolk, 101.
Suffolk, England, 101, 152.
Sumeria, 417.
Surinam, 6.
Surrey, England, 265.
Sussex, England, 145, 152, 208, 261, 265.
Syene (Aswan), on river Nile, 505–6, 510–11.
Syria, 6, 159, 193, 196, 217, 280, 521, 574.

Tabriz, Azerbaijan, Persia, 378, 380.
Taff, river, Wales, 434.
Tanais (Don), river, Russia, 519.
Teheran, Persia, 505.
Terracina, Italy, 311.
Tessino, Italy, 218.
Tewkesbury, Gloucestershire, 457.
Thames, river, England, 422, 425, 441, 456.
Thanet, Isle of, 516.
Thau, Étang de, near Trèbes, R. Aude, France, 465, 467.
Thiers, Puy-de-Dôme, France, 115.
Tholen, Isle of, Zeeland, 320.
Thule, Arctic, 506, 509–10.
Thurii, southern Italy, 272.
Tiber, river, Italy, 280–1, 288, 312–13.
Ticino, river, Italy, 444, 446.
Timgad, Algeria, 279–80, 282.
Toledo, Spain, 115, 350, 521, 584–5.
Tornea, Finland, 553.
— river, Finland, 554.
Toulouse, France, 329, 430, 459, 464–7.
Tours, France, 463.
Trèbes, on R. Aude, France, 466.
Treguanda, 210.
Trent, river, England, 84.
Trento, Italy, 578.
Treves (Trier), Germany, 279.
Trezée, river, France, 460, 462.
Trezzo, on R. Adda, Italy, 446, 448.
Troyes, Aube, France, 371.
Tunis, N. Africa, 480.
Turin, Italy, 280, 286–7.
Turkey, 4, 8, 405, 579.
Tuscany, Italy, 218, 314–15, 677.
Tyne, river, England, 74, 76.
Tyrol, Austria, 341.
Tyrone, Northern Ireland, 455.
Tyrrhenian Sea, 311.

Udine, Italy, 286.
Ufenti, river, Italy, 311.
Ulm, Germany, 532.
Ur, Mesopotamia, 271.
Urbino, Italy, 311.
Utrecht, Holland, 197, 441–2.

Valencia, Spain, 210.
Väner, Lake, Sweden, 455.
Vann Farm, near Chiddingfold, Surrey, 207.
Vatican City, 196.
Vatter, Lake, Sweden, 455.
Venice, Italy, 209, 216, 222, 230, 234, 238, 245, 248–9, 286, 309, 314, 380, 405–6, 424, 430, 441 n 2, 472–4, 476, 479, 526, 598, 678, 681, 703, 705.
Vernassonne, stream, Languedoc, canal, 464.
Verona, Italy, 199, 309.
Versailles, near Paris, 238, 543.
Verulamium, St Albans, Hertfordshire, 277–8.
Vesuvius, Italy, 274.
Vettabia di Milano, Italy, 309.
Vicenza, Italy, 249.

Vicopisano, on R. Arno, Italy, 448.
Vigevano, Lombardy, 286.
Villefranche, near Toulouse, France, 459, 464.
Villepinte, near Castelnaudary, France, 467.
Virginia, 1–2, 9.
Vitry-en-Perthois, Marne, France, 290.
Vitry-le-François, Marne, France, 289–90.
Vosges Mountains, France, 538.
Vreeswijk, Holland, 442, 444.

Wakefield, Yorkshire, 458.
Waltham Abbey, Essex, 451.
Wart, the, Holland, 321.
Wash, the, England, 315, 320.
Watling Street, England, 277–8.
Weald of Kent, 31–2.
Weaver, river, England, 458.
Weidgreb, the, Holland, 302.
Welland, river, England, 316.
Wenlock, Shropshire, 688.
West Africa, 4.
West Indies, 3, 6–7, 159–60, 477, 557, 694.
Westminster, London, 80, 425, 686.
Westmorland, England, 152.
Wettingen, near Zürich, Switzerland, 428.
Wey, river, England, 456.
Weybridge, Surrey, 456–7.
White Horse, Vale of the, Berkshire, 147.
White Sea, the, 533.
Willebroeck, Flanders, 452–3.
Wilton, Wiltshire, 241.
Wiltshire, England, 147, 152, 262.
Winchelsea, Sussex, 284.
Winchester, Hampshire, 277.
Winsford, Cheshire, 458.
Witham, river, England, 316, 516.
Wollaton, Nottinghamshire, 82, 84.
Woolwich, London, 367, 478, 485, 487, 702.
Worcester, England, 201, 688.
Worcestershire, 264.
Wroxeter, Shropshire, 278.
Wye, river, England, 458.

Xativa, Spain, 412.

Yangtze, river, China, 439.
Yellow River, China, 439–40.
Yèvre, river, France, 450.
York, England, 118, 241, 277–8, 284, 544.
Yorkshire, England, 101, 152, 184, 260, 263, 265–6, 458, 689.
Ypres, Flanders, 454.
Yser, river, Flanders, 454.

Zaan, river, Holland, 106.
Zeeland, Holland, 301, 303, 318.
Zuid Beveland, Holland, 301.
Zuyder Zee, Holland, 293, 485.

III. INDEX OF SUBJECTS

Abacus, 501.
Académie des Sciences, 345, 553, 718.
Accadèmia del Cimento (1657), 315, 636–7.
Accadèmia Fisicomatematica, 312.
Acids, 65, 176, 407, 706.
  mineral acids, 678.
  nitric acid, 12, 39, 63 n, 65, 695, 706.
  sulphuric acid, 12, 176.
Admiralty, British, *and* nautical instruments, 557.
Adzes, 107–8, 110, 117.
Aeolipile (steam injector pump), 52–3.
Agriculture, 12, 14, 677.
  arboriculture, 13–14.
  artificial grasses, 12.
  books on, 14.
  crops, 12–15.
  fertilizers, 13.
  livestock, 12, 15.
  market-gardening, 13–15.
  processes, 14–15, 134–8.
  scientific investigations, 679.
  tools, 14–15, 134–9.
  vehicles, 139–48.
  viticulture, 13.
Albumen, 29.
Alchemy, 27, 676, plate 28.
Alcohol, 2.
  testing, 21–2.
Alidade, 538–41, 589–90, 593, 606–7, 627.
Alloys, 37–49, 51, 55, 58, 237, 361, 364, 393.
Almagest, Ptolemy's 'System of Astronomy', 508, 566, 584, 586–9, 591, 612, 615.
Almanacs and calendars, 535, 552–3.
  Connoissance des Temps, 553, 557.
  'Mariner's New Kalendar', 553.
  'Nautical Almanac', 557.
  'Seaman's Kalendar', 552.
Alum, 41, 77, 706.
America:
  architecture, 253; weather-boarded houses, 265.
  coal, 86.
  cochineal, 695.
  cotton, 159.
  discovery, 548.
  flax, 156.
  iron, 32.
  name, 535 n.
  printing, 390, 401.

America (*cont.*):
  rice, 5.
  spinning-wheel, 161.
  voyages, 477.
Annealing, 55–6, 207, 215, 225, 227 238–9, 367, 410.
'Antikythera' machine, 617–18.
Antimony, 29 and n, 34, 39–44, 46, 58, 237, 393,
  smelting, 51.
Antiquaries, Society of, 436.
Anvils, 111, 113, 352.
Apparatus, scientific, 642–7.
Apprentices, 112.
Aqueducts, 289, 446, 466–7.
Arabs:
  astrolabe (1223-4), 614.
  astronomy, 508, 584.
  cartography, 521–2.
  knitting, 182.
  and meridian, 553.
  numerals, 501–2.
  scientists and specific gravity, 22.
  texts on equatorium, 616.
  see also Islam, Muslims.
Archery, 351–3.
Architecture:
  engraved drawings, 409.
  French Academy of, 256.
  Gothic, 245–7, 252, 257, 265, 267.
  Greek and Roman 'orders' of columns, 246–7, 253, 256, 260.
  Renaissance, 245–6, 248–9, 252, 256–7.
  Roman, 245–7, 256.
Architecture hydraulique (1737–53) of Belidor, 324, 422.
Arithmetic, 501, 542.
Armillary:
  astrolabon, 591–2, 606, 613.
  equatorial or equinoctial, 587, 589.
  meridional, 588–9.
  sphere, 613, 625.
Armour, 350, 352–4.
  hardening of, 34–5.
  screws in, 629.
Ars vitraria experimentalis (1679) of Johann Kunckel, 222, 224.
Arsenic, 29, 38, 40–2, 45–6, 226, 229, 237.
Artillery:
  breech-loading, 361–2.
  cannon, 31, 34, 54, 360–8, 374–5.
  field-guns, 347–50.
  mortars, 368–9.
  naval guns, 350, 363, 473, 478–81, 499.
  ranges and range-finding, 361, 367, 537.
  trunnions, 362, 365.
  see also Guns
Artisans:
  carpenters, 111, 113, 117–18, 487, 491–2, 623.
Artisans (*cont.*):
  chairmakers, 118.
  coachbuilders, 113, 118.
  coopers, 112–13, 118, 128–32.
  cutlers, 115.
  farriers, 111, 113.
  glass-painters, 116.
  gold-beaters, 116.
  goldsmiths, 406.
  joiners, 123, 623.
  masons, 111, 435.
  pewterers, 116.
  printers, 386–90, 394–5, 402–3, 409.
  sawyers, 112, 487.
  scientific and mathematical instrument-makers, 585–6, 609, 613, 621–5, 629–31, 642.
  shipwrights, 117, 120, 476, 479, 487–8, 492, 494.
  spur- and bit-makers, 116.
  turners, 343, 623.
  violin-makers, 116.
  wainwrights, 145.
  watch-makers, 120.
  wheelwrights, 111–12, 117–18, 123–8.
  wood-cutters, 404.
  see also Glass-workers, Smiths.
Assaying, 27–9, 42–3, 46–7, 59–68.
  equipment, 602.
Assyrians, *and* seven-day week, 565.
Astrolabes, 513, 521–2, 526, 528–9, 536–7, 540, 585, 603–9, 614, 625, 636.
  mariner's astrolabe, 546, 549, 608–9, 625.
  plane astrolabe, 605–9.
  texts on, 603, 605, 608–9.
Astrology, 565.
Astronomers:
  Alexandrian, 583–4, 586, 599.
  Alfonsine, 592.
  Babylonian, 582.
  Merton College, 585, 593, 617.
  Muslim, 599, 608–9, 612, 615.
Astronomy, 508, 517, 535, 581, 615.
  astronomical instruments, 535–6, 545, 582–94, 614–18, 625.
  astronomical observations, 556–7, 582–4.
  astronomical phenomena *and* calendar, 558–75, 577–81.
  planetary models, 615–18.
  see also Tables.
Athanor, 53, 680.
Athenians, chronology, 572.
Augers, 108, 110, 114, 119, 329.
Awls, 110.
Awners, 139.
Axes, 107–8, 110, 117–19.
Axles, 326, 328, 330, 332.

Back-staff, 551–2, 636.

Babylonian Empire, calendar, 566–8.
Balances, 60–1, 66–7.
Balance-spring, 344.
Ballistics, 256, 359–60, 362, 368, 374–5.
  range-tables, 361, 369, 374.
Banking, 30, 713–14.
Barns, for threshing, 137–8.
Barometers, 543, 630, 636.
Barracan, 178.
Barrels and casks, 112, 128–33.
Barrows, 140.
Baskets, 135, 138–9, 142.
Battles:
  Blenheim (1704), 347.
  Lepanto (1571), 350, 473.
  Malplaquet (1709), 350.
  Quiberon Bay (1759), 499.
Bays, 178.
Beads, glass, 55, 698.
Bearings, roller-bearings, 327, 658, 660.
Beer, 10–11, 80.
Belgium:
  canals and river navigation, 451–4.
  flax, 157.
  fragments of medieval silk, 196.
  glass-making, 206, 208.
Bellows, 32, 50–2, 60, 82, 352, 363, 690.
  blacksmiths', 112.
Bells, 39, 58.
  bell-founding, 40, 54–5, 57.
  bell-metal, 38, 41.
  church bells, 108.
Bergwerkbüchlein ('Essay on Mining'), 27.
Bill-hooks, 117.
Bismuth, 29, 34, 41–4, 51, 57, 62.
Blast-lamps, 55.
Blowpipes, 55, 208.
Bodkins, 394.
Bolters, *and* bolting, 16–19.
Bolting-cloth, 18.
Bombazine, 178.
Bombs, explosive, 38.
Books, 380–2, 388, 405.
  Armenian, 405.
  Bibles, 385–6, 388, 404, 413.
  binding, 386, 390, 404.
  Constance missal, 386, 389.
  Fust-Schoeffer psalter (1457), 405.
  'Justinian' (1468), 393.
  Koran, 380.
  Speculum vitae Christi (1487), 399.
'Books of Secrets', 27, 33, 35, 39, 42.
Borax, 62–3.
  bead test, 68, 226, 228.
Brace, 110–11, 114, 117–18, 120.
Brakes, 110.
Brass, 30 n 2, 37, 40–3, 49, 51, 103, 111, 338–40.
  cannon, 361.
Brass (*cont.*)
  for decorative harness, 149.
  foundry, 38–9.
  smelting, 53.
Brewing of beer, 10–11, 80.
Bricks and tiles, 108, 135, 270–1, 273, 278, 285, 293.
Bridges:
  England, Fleet Bridge, 298; Holborn Bridge, 298; Old London Bridge, 419–20, 430, 432; Westminster Bridge, 425–7.
  France, Pont d'Avignon, 418; Pont Henri IV, Châtellerault, Vienne, 430–1; Pont Neuf, Paris, 293, 423–4; Pont Neuf, Toulouse, 420, 430; Pont Notre-Dame, Paris, 333, 423, 430, 432; Pont Royal, Paris, 425.
  Italy, Ponte Vecchio, Florence, 418, 428–30; Rialto, Venice, 424, 430; Santa Trinità, Florence, 424, 429–30.
  Switzerland, Schaffhausen, 427–8; Wettingen, near Zürich, 428.
  Wales, Pont-y-ty-Prydd, 434–6.
Bridges and bridge-building, 291, 293–4, 298, 306.
  arches, 417–18, 420, 424–36.
  caissons, 425–6.
  coffer-dam, 420–6, 433.
  dimensions, 428 n, 429.
  foundations, 420–7.
  houses on bridges, 430, 432.
  piles, 420–7.
  Roman bridges, 288, 417–18.
  tools, 420.
  truss-girder bridges, 417, 426–7.
  types, 417.
  wooden bridges, 417, 423.
Britain:
  adoption of Gregorian calendar, 579–80.
  agricultural vehicles, 140–8.
  coal industry, 72–3, 76–87.
  industrial success, 711–12.
  iron industry, 78–9.
  spinning-wheels, 161.
  textile industry, 151.
  tinplate, 689.
  town-planning in Roman Britain, 277–9.
  window-glass, 237.
Broadcloth, 178.
Brocade, 192, 197.
Brocatelle, 200.
Bronze, 30, 34, 37–9, 338, 340, 342.
  cannon, 361, 363–6.
Bruzz (triangular chisel), 119, 126.
Building construction:
  arches, 246–7, 250.
  books of 16th and 17th centuries, 245, 250, 253, 257.
  cantilevers, 252.

Building construction (*cont.*):
  catenary curve, 258.
  ceilings, 247–50.
  chimneys, 252, 256, 261.
  churches, 246–9, 254–9, 267.
  columns, 247.
  cornices, 247, 249, 256.
  domestic building, 246–7, 249, 252–4, 256–7, 260–5, 267.
  fireplaces, 261.
  materials, bricks and tiles, 247–8, 258, 261–2, 265; lath-and-plaster, 248, 264; masonry, 247, 255, 258, 260; slats, 254, 260; stone, 247, 249, 254, 256–8, 260–1; timber, 248–50, 253–7, 262–6.
  ornamentation, 245, 252.
  roofs, 252–4, 256, 260–1, 263, 265–7; domed, 245–6, 248, 253–5, 258–9; hammer-beam, 264–5; mansard, 249, 253, 265; vaulted, 247–50.
  spires, 265, 267.
  staircases, 257, 267.
  tensile tests, 250–2, 258.
  walls and wall-panelling, 247, 261, 266–7.
  weather-boarding, 265.
  windows, 248, 253, 255–6, 260.
Buildings: Athens, Tower of the Winds, 517, plate 26 A.
  England:
  Banqueting House, Whitehall, 256, 267.
  Canterbury Cathedral, 516, 596–7.
  Chichester Cathedral, 265, 267.
  Christ Church, Oxford, 257.
  Clifford's Inn, London, 266.
  Corfe Castle, Dorset, 369.
  Dover Castle, 651.
  Gloucester Cathedral, 241.
  Great Chalfield Manor, Wiltshire, 262.
  Hampton Court Palace, 245, 253, 262, 264–5.
  King's College, Cambridge, 242.
  Old St Paul's, London, 254.
  Queen's House, Greenwich, 256, 267.
  Royal Exchange, London, 298.
  St John's Church, Leeds, 257.
  St Paul's Church, Covent Garden, London, 256.
  St Paul's, London, 254–5, 258–9, 296–8.
  Salisbury Cathedral, 650–1.
  Sheldonian Theatre, Oxford, 265–6.
  Staple Inn, Holborn, 264.
  Swinsty Hall, Yorkshire, 260, 263, 265–6.
  Tower of London, 298.
  Westminster Abbey, 203.
  York Minster, 241.
  France:
  Fontainebleau Palace, 256.
  Hospital of the Salpêtrière, chapel, Paris, 254.

Buildings (*cont.*):
  France (*cont.*)
  Invalides, second Church of, Paris, 254–5.
  Louvre, Paris, 253, 341.
  St Germain, Château, near Paris, 254.
  SS Paul and Louis, Paris, 254.
  Sens Cathedral, 198.
  Sorbonne, Church of The, 254–5.
  Theatine Church of Ste-Anne-la-Royale, Paris, 254.
  Tuileries Palace, 425.
  Val-de-Grâce, abbey church, Paris, 254–5.
  Visitation, Church of the (later the Calvinist Church), Paris, 254.
  Holland:
  St Servatius, Church of, Maastricht, 202.
  Italy:
  Florence, Cathedral, 245–6, 248, 258; Palazzo Vecchio, 707; Pazzi Chapel, 249–50; Riccardi Palace, 247; Strozzi Palace, 247.
  Padua, Town-hall, 249.
  Pisa, Cathedral, 662.
  Pompeii, 'House of the Faun', 274–5.
  Rome, Farnese Palace, 248; Lateran Palace, 289; Pantheon, 258; St John Lateran, 289; Santa Maria Maggiore, 249–50, 289; St Peter's, 246, 248–9, 255, 258, 289; Sistine Chapel, 248; Temple of Tellus, 504; Theatre of Marcellus, 266; Vatican Palace, 289.
  Venice, Santa Maria dei Miracoli, 248–9.
  Vicenza, Town-hall, 249.
  see also Town-planning, towns described: Babylon, Byzantium, Carcassonne, London, Neubrandenburg, Ostia, Paris, Piraeus, Priene, Rome, Timgad, Winchelsea.
Burden-creels, 140.
Burin, 405–7.
Byzantine Empire:
  architecture, 245.
  scholars, 530.
  scientific instruments, 584.
  silk weaving, 191–2, 195–6, 198.
  sketch-plan of Byzantium, 279.

Calamanco, 178.
Calamine, 30, 37, 690, 692.
Calculating and computing instruments, 627, 636.
Calendar and chronology:
  Alexandrian, 564.
  Babylonian, 566–8.
  Calippic, 571.
  Egyptian, 560–6.
  Greek, 568–72.
  Gregorian, 575, 578–80.

Calendar and chronology (*cont.*):
  Islamic, 580–1.
  Jewish, 572–5.
  Julian, 564, 571, 576–8, 580–1.
  Julian Period, 564, 581.
  Metonic, 570–1.
  Roman, 564, 575–8.
  based on celestial phenomena, 558–60.
  calculators, 614.
  cycle of seasons, 559.
  definition, 558.
  perpetual calendar for movable feasts of Church, 654.
  seven-day week, 565–6, 572–3.
  'styles', 580.
Calenders, 177–8.
Calibrating, 554.
Calico, 178.
Calipers, 110, 120, 512.
Cambric, 164, 178.
Camlet, 171, 178.
Canals, 85–6, 286–7, 291, 294–5, 298, 303, 311–12, 317, 319–20, 373, 438–68.
  culverts, 446, 449, 452–3, 467.
  irrigation canals, 444, 446.
  lateral canals, 440, 464.
  locks, 439, 442, 447–9, 452–7, 460–4, 467; pound-locks, 446, 450–2; tide-locks, 442–4, 451, 453; lock-gates, 439, 442, 445–7, 458, 462; mitre-gates, 286, 447–8, 450–2, 460.
  reservoirs, 463, 468.
  side-ponds, 454.
  slipways, 439, 441 and n 2.
  summit-level canals, 440, 443, 448, 454–5, 462.
  stanches, 440–1, 444, 456, 464.
  traffic, 439.
Canals named:
  Briare (1604–42), 460–5.
  Bereguardo, Lombardy (1452–8), 446.
  Bologna (1491–3), 447.
  de Bourgogne, 459.
  Bruges to Ostend (seventeenth century), 453.
  Brussels, (1550–1607), 450–3, 462.
  Ch'ang-an to Yellow River (133 B.C.), 439.
  Charolais, 459.
  Dunkirk to River Aa (1670), 453.
  Exeter (1567), 451, 456.
  Finow (1620 and 1744–51), 454–5.
  Friedrich-Wilhelm (1669), 454.
  Göta canal (1808–10), 455.
  Grand Canal, China (A.D. 610 and 1280–93), 439–40.
  Lake Hjälmar to River Arboga (1629–39), 455.
  Languedoc (1666–92), 459, 464–8.
Canals named (*cont.*):
  Ling Ch'u in Kuangsi, China (215 B.C.), 439.
  Lys to Scarpe (1692), 453.
  Martesana, Lombardy (1462–70), 446, 448, 450.
  Mecklenburg, 450.
  Naviglio Grande, Lombardy (1260 and 1438), 444–6, 449.
  Naviglio Interne, Lombardy (1497), 445, 448.
  Newry to Lough Neagh (1737–45), 455.
  Nieuwe Rijn, Holland (1148), 441.
  Nile to Red Sea (*c* 510 B.C.), 439.
  Orleans (1682–92), 463–4.
  Paderno, Lombardy, 448–50.
  Padua to River Brenta, 447, 451 n.
  Pien Canal in Honan, China (A.D. 70), 439.
  Plaue, Germany (1743–6), 455.
  Shanyang Canal in Chiangsu, China (A.D. 350), 439.
  Stecknitz, Germany (1391–8), 443–4, 454.
  Stockholm to Göteborg (1610), 455.
  Wey, England (1651–3), 457.
  Ypres to Boesinghe (1643–6), 454.
Cannon, *see* Artillery.
Capitalism: influence on mechanization, 27, 30.
Capstan, 367, 483.
Caput mortuum, 63 and n.
Carat, meaning, 46 n.
Carbon, 33, 63.
Carbonization, 34.
Carmen de ponderibus, 67.
Cartography, 502–10, 515–22, 530–6, 553–5.
  instruments, 553–5.
  meridian, 506, 508–11, 521–2, 531, 533, 535–6, 544, 548–9, 553.
  projective mapping, 505, 508–11, 530–1, 535–6.
  scale-cutting machine, 555.
  stereographic projection, 603–4.
  see also Maps.
Cartridges, 348, 358.
Catenary curve, 258, 434 and n.
Cementation, 27, 33–5, 37, 47, 54.
Ceramics, 60, 678–9.
Chaldeans, *and* calendar, 564, 566–8.
Chamfering, 120–1.
Charcoal, 29, 31–2, 35, 37, 53, 55, 62–3, 342, 350, 683–5.
  need for substitute, 33.
  replaced by coal, 78–81.
Chemical industry:
  materials, 705–6.
  wood-using industries, 683–5.
  see also Dyeing industry, Enamelling, Lacquering, Soap-making, Varnishes and varnishing.

Chemistry:
  analytical, 22, 683.
  early books on, 676–7.
  phlogiston theory, 57.
  practical applications, 677–83.
  quantitative, 28.
  see also names of separate substances.
Chimneys, chimney-stacks, 52, 252, 256, 261.
China:
  adoption of Gregorian calendar, 579.
  bridges, 417.
  canals and river navigation, 438–41, plate 18.
  coal, 73–4.
  cotton, 159.
  draw-loom in the figure-harness, 190–2.
  figured fabrics, 195, 199, 201.
  geographical knowledge of, 507, 524.
  iron industry, 74, 79.
  lacquered ware, 696.
  metallurgy, 691.
  paper money, 380.
  printing, 378.
  silk, satin, damask, 195, 200–3.
  tea, 5.
  windmills, 106.
  zinc, 30, 690.
Chisels, 110–11, 114, 118, 126, 365–6, 404.
Christian era, 572, 578.
Circumferentor or 'Dutch circle', 627, 636.
Clay, used in manufacture of cannon, 363–5.
Clepsydra, *see* Water-clocks.
Clinkers, 226, 228.
Clocks and watches (plate 32):
  alarm, 652.
  anchor-escapement, 664–71.
  astronomical, 653–5, 658.
  dead-beat escapement, 671–3.
  early mechanical clocks, 648–53.
  mercury clocks, 648–9.
  nautical, 552–3, 557, 672–3.
  pendulum, 552, 636, 662–7, 671–2.
  repeating mechanism, 669–70.
  shadow-clocks, 595–6.
  spring-drive, 656–60.
  water-clocks (q.v.).
Clodding-beetles, 134–5.
Cloth, types of, 178–9; *see also* textiles, wool.
Coal and coal-mining:
  in China, 74.
  in medieval Europe, 74.
  in Roman Empire, 72–3.
  briquettes, 80, 679.
  domestic uses, 76.
  industrial uses in seventeenth century, 76–8, 686.
  mines, drainage, 74, 81–3; machinery, 82–4; ventilation, 75.
  production, 77.
  substitute for wood, 78–81, 220–1.
Coal and coal-mining (*cont.*):
  technological significance, 85–7.
  transport, 84–5.
Cobalt, 30, 218, 678, 698, 703; *see also* Smalt, Zaffre.
Cochineal, 695.
Codice Atlantico of Leonardo da Vinci, 161, 172, 175.
Coffee, *see* Drink
Cogware, 178.
Coinage and coins, 45–7.
  assaying, 60.
  blanching, 46–7, 56.
  dies, 338–9, 340.
  techniques and tools, 337–41.
Coke, smelting with, 29, 80, 689.
Colours, 692–8, 702–3.
  assaying, 64, 68.
  colour-knitting, 182, 185.
  oxidation, 49.
  speculum-metal, 40.
  steel, 36–7.
Compasses, drawing, 110, 124, 488, 512, 627–8.
  magnetic, 517, 524–6, 533–4, 538–40, 548–9, 555, 600, 626–8, 630, 637–8.
'Compleat Chymical Dispensatory, The' (1669), 29.
Condensers, 51.
Conduit, built by Hezekiah, King of Judah, 510–11.
Coopering, 128–33, plate 7.
Copper, 27, 29, 33, 40–1, 48, 51, 55, 82–3, 218–19, 340–2, 363.
  alloys, 37–42, 46, 49, 58, 361.
  assaying of ores, 62–3.
  carbonate, 48.
  copper plate engraving, 405, 408–10.
  oxide, 46–7.
  relief blocks for woodcuts, 405.
Copperas (ferrous sulphate), 680, 694, 706.
Cork stoppers, 10.
Cosmography, 535–6.
Cotton, 159–60, 163–4, 169.
  in paper-making, 411.
  Manchester cotton, 179.
  supplies, 159.
Cranes, 420.
Cranks, 423.
Crepon, 178.
Cross-shave for smoothing inside pails, 112.
Cross-staff, or Jacob's Staff, 527–8, 537, 546–7, 591, 625.
Croze, 119.
Cupels and cupellation, 60, 64–5.
Cycloid, work of Huygens on, 345, 663 and n 3.
Cylinders, 332–4, 341, 363, 367–8.
  cylinder-escapement in clocks and watches, 671, 673–4.

Cylinders (*cont.*)
  glazing-cylinders, 414–15.
  rotating cylinders in paper-making machine, 412, 414.

Damask, 165, 192, 199–203, 205.
Dams, *see* Dikes and dams.
De coloribus et artibus Romanorum, attributed to Heraclius, 207.
De re aedificatoria (1485) of L. B. Alberti, 250, 446.
De re metallica of Agricola, 27–8, 82, 206, 212–14, 324, 677.
Decimal system, 61, 542.
Density, assay by, 66–8.
Designs on fabrics, 187–205.
  on glass, 241–2.
Diagrams, engraving of astronomical and mathematical, 405, 409.
Diamonds, used in glass-engraving, 229.
  used in glass-cutting, 233.
Diaper, 178.
Dibbles, 135–7.
Dictionaries for technical information, seventeenth century, 682.
Dictionnaire des Sciences (1765), see *Encyclopédie.*
Die-stamping, 338–9.
Dikes and dams, 293–4, 301–3, 308, 310, 318, 320, 441–2, 452, 468.
Dimity, 178.
Dioptra, 591.
  Hero's, 609–12, 641.
Distillation: 54, 679, 686–7.
  of alcohol, 2, 11–12, 678.
  of mercury, 51.
  apparatus, 60.
Dividing-engines, 641–3.
Dorsal-car, 140–1.
Dowlas, 178.
Drainage and reclamation of land:
  administrative organizations, 308, 319, 322.
  dikes, 301–3, 308, 310, 318, 320.
  drainage-mills, 303–7, 317, 321–2.
  drying of inland meers, 302–6, 308, 320.
  fen drainage, 315–22.
  flood-gates and sluices, 302–3, 305–6, 312, 320.
  marsh drainage, 311–13, 318–19.
  polders, 301, 304, 306, 310, 320.
  pumps, 303–5, 307, 321–2.
    centrifugal pumps, 308; piston-pumps, 304.
  river regulation, 308–16, 318–20.
  scoop-wheel, 303–6, 321–2.
  sea-defences, 300–2, 308, 316.
  treatises on, 301, 305, 307, 310, 312, 314–15, 317, 320–1.
Draw-plates, 47.
Dredgers, 420, 425.
Drills: 110.
  beam-drill, 114.
  for seed-sowing, 135–6.
Drink:
  alcoholic, 10–12, 21–2.
  ale, 23.
  beer, 10–11, 80.
  cider, 10.
  chocolate and cocoa, 5–6.
  coffee, 1, 5–6, 23.
  milk, 23–4.
  spirits, 11, 23.
  tea, 1, 5, 23.
  wine, 11.
Drugget, 179.
Drugs:
  coca-leaf, 1.
  guiaeum, guaiacum, 1.
  Indian hemp, 1.
  ipecacuanha, 1.
  opium, 1.
  quinine, 1.
Dry-point engraving, 406–8.
Dust, protection from, 351.
Dyeing industry, 77, 679, 681, 692–5.
  insect dyes, 695.
  plant dyes, 692–4.
Dynamics, 344–5.

Earth:
  shape and size, 504–6, 518–22, 544, 553–4, 613.
  and calendar, 558–9.
Easter, dating of, 578–9.
Egypt:
  bridges, 417.
  calendar, 560.
  canals and river navigation, 438–9.
  chronology, 564–5.
  coffee, 5.
  dials, 595–7.
  figured fabrics, 194, 196–7.
  knitting, 181–3.
  printing, 380.
  shadow-clock, 595–6.
  sugar, 6.
  surveying, 502, 510.
  tapestries, 195.
  town-planning, 269–70.
  water-clocks, 601.
  weaving, 193.
Elasticity:
  'Hooke's Law' of, 257.
  mathematical, 58–9.
Electrical machines, 638, 644.
Electrolytic corrosion, 45.
Embroidery, 182.
Enamel, *see* opaque glass, under Glass.

Enamelling, 55, 692, 695, 697–9.
Encyclopédie (1751–76), 204, 226, 360, 367.
Engineering:
  civil engineering, 373, 459, 468.
  fortification-engineering, 370–3.
  light engineering, 325, 334, 340, 345.
  precision-engineering, 629, 641–2, 647.
  progress in sixteenth and seventeenth century, 325.
  science and engineering, 344–5.
Engines:
  rotary-engine, 84.
  steam-engines, 83–4, 330, 344, 368.
England:
  agriculture, 14–15, 134–9; agricultural vehicles, 140–7.
  alcoholic spirits, 11.
  archery, 348, 351–2.
  astrolabes, 609.
  brass-making, 37.
  bridges, 418–20, 425–7, 430.
  building, 245, 247, 252–3, 256–67.
  canals and river navigation, 438, 441, 451–2, 456–8.
  cartography, 522.
  clocks, 553, 663–4, 674.
  coal, 73–4, 685–6, 688–9.
  coinage, 46.
  cotton industry, 159–60.
  cropping-machines, 174.
  date of New Year's Day, 580.
  diet, 1, 3, 5–6, 8, 24.
  dyeing industry, 694–5.
  flax, 158.
  fulling, 171.
  gig-mills, 172.
  glass-making, 86, 206–9, 216–23, 225–34, 237–42, 700, 702–3.
  iron industry, 31.
  japanning and lacquering, 696–7.
  knitting, 184–6.
  land drainage and reclamation, 300, 308–9, 315–22.
  navigation, 550–7.
  paper-making, 416.
  printing, 392, 399, 409–10.
  railways, 85.
  science, impact on industry, 679–83.
  scientific instrument-making, 585–6, 621.
  ships, 475, 477–88, 490–2, 494, 496–9.
  silk, fragments of medieval, 196.
  soap, 703.
  spinning-wheels, 161–2.
  steam, 687.
  sun-dials, 596–7.
  surveys, 516, 541–3.
  textile industry, 163, 173.
  tinplate, 689.
  tobacco, 8–10.
England (*cont.*):
  town-planning, 277–9, 284, 295–8.
  velvet, 205.
  wars, 349, 369.
  weaving-looms, 164–5, 167–70.
  windmills, 89, 91, 93–107.
  wood, distillation, 685; substitutes, 685–9.
  wool, 151–3.
Engraving, 405–8, 586, 623.
  tools, 407–8, 624.
Ephemerides, 503, 535, 547, 552.
Equatorium, 616–18.
Esparto grass for paper-making, 415.
Etamine, 179.
Etching, 406–8.
Evaporation, 54.
Explosives, 355, 374.
  see also Gunpowder.
Eyes, artificial, 699.

Factory system, 151–2.
'Feed-back' mechanism, 680.
Felt, 186.
Fertilizers, 13.
Feuerwerkbuch (1454), 34.
Figure-harness, 187–95, 197–8, 201–3.
Files, 110, 343, 352, 365.
Firearms, 347–50, 354–69. *See also* Artillery, Guns.
Fire-grates, 20.
Flails, 134, 137.
Flanders:
  adoption of Gregorian calendar, 579.
  canals and river navigation, 441 n 2, 452–4.
  diet, 6.
  dyeing industry, 694–5.
  stained-glass windows, 241.
  weaving, 159.
  windmills, 93, 95, 97.
Flannel, 179.
Flax, 156–8, 160, 163–4.
Fluxes, 39, 41, 48, 62–3.
  in glass-making, 206–7, 209–10, 217, 226–8.
Fodder, 5, 12–13.
Food:
  adulteration, 20–2.
  analysis, 20–2, 24–5.
  buckwheat, 5.
  butter, 14, 23–4.
  cheese, 23–4.
  cooking, 19–20.
  diet, 1, 7, 19, 22–5.
  digestion of food, 24–5.
  eating habits, 19–20.
  eggs, 23.
  fish, 22–4.
  flour and bread, 15–19, 23.
  fruit, 23–4.

Food (*cont.*)
  honey, 6.
  maize, 1, 3–4, 13.
  meat, 12, 23–4.
  potatoes, 1–3, 12–13, 23.
  preservation, 22, 679.
  rice, 1, 4–5.
  sugar, 1, 6–8, 23.
  turkey, 1.
  vegetables, 19, 23–4.
Forces, 432–3.
Forges, 34, 78–9, 352, 684.
  Catalan forge, 52.
  hammer-forges, 32.
  smith's forge, 51–2, 62–3, 350.
Forks:
  agricultural, 134, 137.
  table, 20.
Fortifications, 276–8, 282–4, 286–7, 290, 294–5, 349, 369–73.
  castles, 369–70.
  treatises, 256, 370.
Fossilia, 28 n 1.
France:
  Academicians, 544.
  adoption of Gregorian calendar, 579.
  agriculture, 12–13.
  bridges, 418, 420, 423, 425, 430–1.
  building, 247, 252–7, 262.
  canals and river navigation, 86, 439, 441, 448, 450, 459–68.
  cartography, 544, 554.
  ceramic industry, 678–9.
  clocks, 651, 674.
  coal, 72, 86.
  coinage, 341.
  diet, 2, 5–6.
  dyeing industry, 695.
  flax, 156.
  fortifications, 372–3.
  fragments of medieval silk, 196, 202.
  fustian industry, 159.
  glass-making, 86, 206–8, 214–15, 237–41, 677.
  iron consumption, 31 n 1.
  knitting, 183, 185–6.
  lacquering and japanning, 696–7.
  land drainage and reclamation, 300, 309, 318–19, 322.
  navigation, 553, 557.
  paper-making, 415–16.
  printing, 384, 392, 397–8.
  scientific instruments, 585, 621.
  ships, 478, 483, 485, 496.
  silk, 165.
  soap, 703.
  spinning-wheels, 161.
  survey, 540, 543, 554.
  textile industry, 170–5, 178.
France (*cont.*):
  tinplate, 689.
  tobacco, 8, 10.
  town-planning, 283, 290–3.
  water-wheels, 328–9.
  weaving-looms, 164–9.
  windmills, 89–93, 95–7, 99, 101–5.
  wool, 152, 177.
Friction-band, adjustable, 161.
Froe *or* rending-axe, 119.
Fuel economy, 686.
Fuller's earth, 169–71.
Fumifugium (1661) by John Evelyn, 296.
Furnaces (frontispiece; plate 3):
  automatic (athanor), 53, 680.
  'beehive', 685–6.
  blast-furnaces, 30, 31–4, 50, 52, 79–81, 363.
  brick, 53.
  coal-burning, 78–9, 86, 221.
  glass-making, 78, 86, 207–14, 217, 220–1, 226, 238–9, 699–700.
  muffle, 600, 698.
  open-shaft, 49.
  reducing, 49–51.
  reverberatory, 27, 49, 54–5, 80, 210.
  self-stoking, 53, 55.
  solar-furnaces, 55.
  thermostatic control, 679–80.
  wind-furnaces, 51–2.
Fustian, 159, 171, 179.

Garments, knitted (plate 9):
  berets, 186.
  caps, 181, 186.
  hose, 186.
  sandal-socks, 181–2, 184.
Gauges, 112–13.
Gears, 235, 325, 328.
  gear-wheel teeth in clocks, 345.
Geographike syntaxis of Ptolemy, 502, 509, 530.
Geography, 502–3, 505, 507–9, 517.
Geometry, 502, 520, 528, 537.
  geometrical optics, 633.
Gerard's 'Herball', 1–3.
Germany:
  adoption of Gregorian calendar, 579.
  agriculture, 12.
  brass-making, 37.
  canals and river navigation, 441, 443, 449–50, 454–5.
  cartography, 534–9.
  chemistry, 682.
  coal, 82.
  diet, 2–3, 5–6.
  dyeing industry, 694.
  figured silks, 196.
  flax, 156.
  fulling-stocks, 170.

Germany (*cont.*):
  glass-making, 206, 220–2, 224–5, 229, 237–8, 240–1, 700.
  hemp, 158.
  houses, half-timbered, 257.
  ink, 381.
  iron, 31 n 1, 689.
  japanning, 696.
  knitting, 186.
  maps of Germany, 533–5.
  mining and metallurgy, 678.
  playing-cards, 380.
  printing, 377, 382–5, 388–90, 404, 406–7.
  railways, 84–5.
  rifles, 358.
  scientific books, 677.
  scientific instruments, 585, 609, 613, 621–2.
  Thirty Years War (1618–48), 349, 622.
  town-planning, 284–5.
  windmills, 97, 99, 106.
  zinc, 691–2.
Gig-mills for raising cloth, 172–3.
Glaskonst ('Art of Glass') of Peder Månsson, 209–10, 212.
Glass and glass-making (plates 16, 30): 206–44, 698–702.
  apparatus and tools, furnaces, 78–9, 86, 207–14, 217, 220–1, 226, 238–9, 699–700; glass-maker's 'chair', 219–20; tools, 208, 210–12, 217, 219–20, 222–9, 231–2, 234–6.
  Bohemian, 206, 220–3, 209.
  books on, 206–7, 209–15, 217–19, 222, 226, 230–1, 698.
  colours, 209–10, 214–15, 218–19, 224, 229, 240–2.
  fluxes, 206–7, 209–10, 217, 226–8.
  glass-houses, for manufacture, 206–7, 214–15, 224–5, 226–8.
  kinds of glass, crown, 240; crystal, 209, 215, 221–2, 702; flint, 86, 678, 702; gold-sandwich, 229; lead, 219, 225; opaque 215–16, 219, 224, 229; optical lenses, 229–37, 699; plate and sheet, 237–40; ruby, 224–5, 229; vessel, 20, 208, 214, 222–3, 228, 698; window, 209, 237–42, 699.
  techniques, up to about 1550, 206–16; from 1550 to eighteenth century, 216–29; cane-techniques, 216; cutting, 225–6, 233; decorative, 214–16, 222–5, 229.
  Venetian, 209, 216, 222, 230, 231, 678.
Glass-workers: 212, 217, 219–20, 223, 226, 229–30, 238.
  Florentine glass-blowers, 636.
Glazing, 261, 695.
Globes, 612–14.
Glockendon Bible of 1524, 160.
Gnomon, 560, 594–6.
Gold, 27, 29, 33, 47, 53, 342.
  assaying, 59, 63–8.
  gilding, 48; glass pigment, 224–5; gold-beater's skin, 48; gold-leaf, 48–9; machine for treating gold ores, 327; powdered for paint or ink, 49; refining techniques, 47–9; spun, 48; thread, 192, 205.
Gouges, 404.
Graphometer, 627, 636.
Greece, modern, adoption of Gregorian calendar, 579.
Greeks:
  architecture, 246.
  astronomy, 520, 566, 612, 615, 620.
  calculations, 501–2.
  calendar, 568–72.
  cartography, 504–7.
  geographers, 613.
  geometry, 502, 520.
  mathematics, 502, 505, 520, 620.
  navigation, 517.
  reckoning-apparatus, 501–2.
  science, 584, 615, 618.
  scientific instrument-making, 618.
  surveys and surveying, 502, 510–11.
  town-planning, 271–5.
Gresham College, London, 257, 681.
Grindstones, 110, 115.
Grogram, 179.
Groma (surveying instrument), 511–12.
Gunnery techniques, 627–8.
Gunpowder, 347–8, 350, 355, 359–62, 366, 368, 684.
  test, 21.
Guns:
  air-guns, 359.
  barrels, 356–9.
  caliver, 354.
  casting, 38–9.
  field, 347–50.
  firelock, 354.
  flint-lock, 347, 354, 356.
  gun-flints, 356.
  gun-locks, 355–6, 360.
  hand-guns, 347–8, 351–60, 362 n.
  harquebus, 352, 354, 367.
  matchlock, 354–6, plate 17.
  muzzle-loading gun, 347, 355.
  muzzle-velocity, 356, 360.
  naval, 350, 362–3.
  pistols, 348–9, 355, 358–9, 362 n.
  rifles, 358.
  sporting-guns, 354, 358, 360.
  wheel-lock, 355, 358, plate 17.

Hacks, for breaking clods, 134–5.
Hammers, 49, 82–3, 110, 342–3, 352, 358, 365, 387, 422.
  glazing-hammers used in paper-making, 414.

Hammers (*cont.*):
  power-driven hammers, 341, 350, 690.
  tilt-hammers, 32, 115, 689.
'Handmaid to the Arts, The' (1758), of R. Dossie, 226, 228.
Harness, 148–9.
Harrows, 134.
Healds, 187 n, 188, 191–3, 195, 197–9, 201–3.
Heddles, 164, 166, 187 and n.
Hemp, 158–9, 174, 176.
Herbals, 1–4, 8.
Hodometer, 512–13, 628.
Hoists, 30, 32.
  power-driven, 105.
Holland:
  adoption of Gregorian calendar, 579.
  alcoholic spirits, 11.
  brick-work, 262.
  canals and water navigation, 441–2, 444, 452.
  cannon, 367.
  diet, 5, 23.
  dyeing industry, 693, 695.
  fragments of medieval silk, 196, 202.
  glass-engraving, 229; glass-making, 700.
  ink, 381.
  japanning and lacquering, 696.
  knitting, 186.
  lens-making, 231–2, 234, 236.
  paper-making, 412, 414–15.
  printing, 383–5, 592–3, 400–1, 409–10.
  ships, 482–3, 485, 496–8.
  spinning-wheels, 161.
  States-General and determination of longitude at sea, 662.
  textile industry, 151, 156–9, 170, 174–5.
  town-planning, 293–5.
  wars with English and French, 349.
  weaving-loom, 164, 167–8.
  windmills, 89, 96, 98–9, 106–8.
Hooks, agricultural, 136–7.
Hoppers, 53.
Hops, cultivation of, 14.
Horologium (1658) of Huygens, 344, 663.
Horologium oscillatorium (1673) of Huygens, 663.
Horses:
  cart-horses, 148–9.
  pack-horses, 139, 141–2, 417.
Horse-power, 45, 82–4, 162, 170, 172, 178, 317, 322, 340, 342.
Horticulture, 13.
Houses, 269–74, 277, 281–4, 291, 293–6.
Hydraulics, 302–3, 309–10, 312–15.
Hydrochloric acid, 12.
Hydrodynamics, 303, 319.
Hydrometer, 12, 22.
  float (Boyle's), 68.
Hydrostatics, 303, 305.
Incubator, 679–80.
India:
  architecture, 249.
  cotton, 159–60.
  figured-silk weaving, 193.
  lacquering, 696.
  steel (*wootz*), 35.
  town-planning, 270.
  voyages to, 476–7, 506–7.
  zinc, 30.
Ink, *see* Printing.
Instruments, precision and scientific, 325, 337, 345, 400.
  books on making, 645.
  computation and demonstration, 612–18, 644.
  materials for, 623, 625.
  production specialization, 629–31.
  see also Astronomy, Cartography, Lenses and optical instruments, Measuring instruments, Navigation, Observatories, Sighting, Surveying, *and names of separate instruments.*
Ireland:
  agriculture, 3.
  alcoholic spirits, 11.
  canals and river navigation, 455.
  coins, 46.
  diet, 1–3.
  farm-vehicles, 140.
  flax, 156–8.
  linen bleaching, 175–6.
  Ptolemy's map, 508.
  spinning-wheels, 160–2.
  wool, 152.
Iron and iron industry (frontispiece; plate 2), 27–9, 42, 44, 50, 115, 218–19, 342–3.
  assaying of ores, 62–3.
  bar, 31–2, 350.
  in building, 258–9, 267.
  cannon, 34, 361, 363, 365–7.
  carbon-content, 33.
  cast, 31–4, 63, 340, 343.
  coal, 78–81.
  consumption, 31.
  domestic implements, 31, 38.
  expansion of industry in 16th and 17th centuries, 326.
  pig-iron, 31–2, 78.
  prices, 30.
  puddling, 81.
  rudder fixtures, 45.
  sheet-iron, 32, 355, 689.
  sponge iron, 33–4.
  wrought iron, 32–3, 79.
  see also Forges, Furnaces.
Islam:
  calendar, 580–1.
  designs on fabrics, 200.

Islam (*cont.*):
  paper-making, 378.
  silk, 191, 197, 199.
  see also Arabs, Muslims.
Italy:
  adoption of Gregorian calendar, 579.
  bridges, 418, 424, 428–30.
  building construction, 245–52.
  canals and river navigation, 441–2, 444–51.
  diet, 2, 5–6.
  ducats, 46.
  dyeing industry, 679, 694.
  fragments of medieval damask, 202.
  fulling-stocks, 170.
  glass-making, 206, 209–20, 230–2, 234, 238, 678, 700.
  hemp, 158–9.
  jewellery, 677.
  land drainage and reclamation, 300, 308–15.
  majolica and porcelain, 678.
  navigation, 526.
  paper-making, 415.
  printing, 390, 406–7, 409.
  Renaissance, 245.
  satin and silk industry, 165, 196, 199, 200, 203.
  scientific books, 677.
  scientific instruments, 585–6, 621.
  soap, 703, 705.
  superiority in science and technical achievement, 710–11.
  velvet, 205.
  weaving, 159.

Jacks:
  clock-jack, 652 and n.
  door-jack, 337–8.
  lifting-jacks, 107–8.
  screw-jack for raising cannon, 368.
Jacquard loom, 167, 187, 201.
Jewellery, 45, 629, 698, plate 29.
  assaying, 60.
  foils under gems, 49.
  jewels in watches, 670–1.
Jews:
  calendar, 572–5.
  chronology, 575.
  and seven-day week, 565, 572–3.
Joinery, 266–7.

Kersey, 179.
Knitting and knitted fabrics:
  Arabic colour-knitting, 182.
  coloured fabric, 185, plate 9 A.
  embossed, 186, plate 9 C.
  felted, 186.
  Florentine knitting, 185, plate 9 B.
Knitting and knitted fabrics (*cont.*):
  frame-knitting, 182–5.
  knitting-needles, 183–5.
  knitting-sheaths, 184.
  lace fabrics, 185–6.
  machine, 185–6.
  needle-weaving, 181.
  Peruvian needle-knitting, 182.
  sprang, 181–3, plate 8 B.
Knives, 110.
  draw-knife, 121.
  knife-blades, 343.
  long-handled, 136.
  table, 20.

Lace, 185–6.
Lacquer industry, 688, 695–7.
Ladles, 52.
Lathes, 235–7, 334–7, 343, 345, 365.
Lead, 27, 29–30, 37–8, 40, 42–5, 48, 51, 58, 342.
  assaying of lead ores, 62.
  bells, 340.
  cast, 34, 45.
  Goslar lead ores, 51.
  lead-crystal, invented, 221.
  lead sulphide, 221.
  for pumps, 332.
  roofing, 44, 254.
  seals, 338.
  sheathing boats, 45.
  sheet, 32, 45.
  shot, 45.
  window strips, 41–2, 44, 256, 261.
Lenses and optical instruments, 229–37, 627, 630–5, 699.
  achromatic lens, 233, 555.
Levels:
  plumb-bob level, 375.
  spirit-level, 375.
  water-level, 609–12.
Levers, 18, 173, 177, 236, 330, 359.
Leyden jars, 644.
Liber Archimedis de ponderibus, 66.
Libraries:
  Cairo, 63.
  monastic, 381.
  St. Andrews University Library, 667.
  St. Bride Technical Library, London, 410.
Libros del Saber Astronomica of Alfonso X of Castile (1252–84), 616, 648.
Lighthouses, *Pharos* of Alexandria, 275.
Linen, 151, 156, 164, 168–9, 174–7, 195–7.
  in paper-making, 411.
Linsey-woolsey, 179.
Liquation process, 27, 33, 42, 51.
Litharge, 63–4, 697.
Logarithms, 542, 553.

London, plans for rebuilding after Great Fire, 297–8, 320.
  Roman, 278–9.
  seventeenth century, 295–6.
  Squares, 296, 298.
London livery companies:
  Clockmakers, 630.
  Pewterers, 42, 68.
  Spectaclemakers, 630.
Looms, 151–2, 164–9, plate 8 A.
  draw-looms, 164–7, 187–9, 191–5, 202.
  opposition to power-looms, 167–8.
Low Countries:
  coal, 72–4.
  farm wagons, 146.
  iron industry, 79.
  printing, 401.
  scientific instruments, 586, 621.
  windmills, 89, 93–5, 100–1, 106.
Luttrell psalter, 142–3.
Lye, for soap, 704.

Machinery and machines, 324–45.
  armour polishing, 350.
  bearings, 41–2, 327, 658, 660.
  cannon- and gun-making, 359, 365, 367.
  chain-and-bucket pump, 325–7.
  characteristics in sixteenth and seventeenth centuries, 324–6.
  drainage, 82–3.
  gudgeons, 41–2.
  lens-making, 232, 234–6.
  mechanization of power, 19.
  metals used, 326.
  oil, 42.
  ore-crushing, 327–8.
  paper-making, 411–16.
  pile-driving, 422.
  rolling, 338.
  scale-cutting in cartography, 555.
  slitting, 338.
  steam-driven, 85.
  textile, 152–5, 157–9, 162–78.
Majolica, 678.
Mallets, 110, 119, 126.
  caulking-mallet, 120.
Mandeville: 'Sir John Mandeville's Travels', illustration of glass-furnace, 207, plate 16.
Mandrel, 335–7.
Manganese, 115, 210, 218, 222, 702.
Maps, 405, 409.
  based on triangulation, 554.
  'Carte Pisane', 523–4.
  'Catalan Atlas', 525.
  Claudius Clavus's map of Scandinavia, 532–3.
  contoured, 555.
  hachuring, 555.
  Hereford map, 519–20.
Maps (*cont.*):
  isometric, 555.
  regional maps, 537–9.
  road maps, 534–5, 539.
  star maps, 604–5.
Marcasite, 30.
Margarita philosophica, university textbook, surveying instruments, 538.
Mass-production, 709–10.
  flour, 19.
  scientific instruments, 629.
  small bronze objects, 39.
  tools, 113–14.
Matches: slow-match, 355 and n 2.
Mathematics, 502–3, 505, 536, 539.
  applied to fortification, 371–2; navigation, 526; projectiles, 374–5; shipbuilding, 482, 488.
  mathematical analysis, 615.
  mathematical elasticity, 58–9.
  mathematical instruments, 521, 627, 636, 644.
  mathematical theory, 257, 344.
  see also Tables.
Mattocks, 134.
Measurements and mensuration, 537–41, 555.
  Pantometria of L. Digges, 541.
  units, acres, 528; chains, 542; German mile, 535–6; Italian mile, 535–6; knots, 550; Roman mile, 506, 517, 522, 535; sea-miles, 550; stade, 505–6, 522, 531.
Measuring instruments, 336, 375, 386, 627.
  for time, 594–8, 601–3.
  see also names of separate instruments.
Mechanics, study of, 250, 252, 433.
  of clocks, 345.
  of projectiles, 374–5.
Medallions and medals, 39, 338–9, 341.
Medicine and surgery: military, 374.
Mercator chart, 550–1.
Mercator's projection, 548.
Merchants' tokens, 46.
Mercury, 33, 40–1, 327–8.
  assaying, 62.
  clocks, 648–9.
  smelting, 51.
  see also Barometers.
Merton College, Oxford:
  astronomers, 585, 593, 617.
  medieval equatorium at, 617.
Metallurgy and metals:
  assaying for base metals, 59, 62–5.
  bearing-metals, 41–2.
  for cannon, 361, 363.
  density, 57–8.
  engraving, 405–8, 623–4.
  fractures, 57–8.
  German pre-eminence in sixteenth century, 678.

Metallurgy and metals (*cont.*):
  interaction of metals, 58–9.
  in machines, 326, 328, 330, 332, 336–7.
  manufacture of metal goods, 678.
  mechanization, 30, 340–1.
  non-ferrous, 50–1.
  plating, 42.
  precious, 63–8.
  printing, 43, 385, 393, 405–8.
  refining, 42.
  sheet-metal, 340.
  structure, 57.
  tensile properties, 58–9.
  treatises, 27–9, 33, 63, 68, 79.
  see also Smelting, *and names of separate metals.*
Mezzotints, 406–8.
Micrometer, 640, 644. 630–5.
Microscopes, 21, 41, 57, 232–3, 336, 554,
Milling flour, 15–19.
Mills:
  churn-mill, 14.
  drainage, 106, 303–7, 317, 321–2, plate 20.
  frizing-mill, 176.
  gig-mills, 172–3.
  glass-grinding, 239.
  horse-mill, 688, 702.
  roller-mills, 16–17, 19, 32, 41, 45, 47, 341–3.
  saw-mills, 106–7, 308.
  slitting-mills, 32.
  stamping-mill in paper-making, 412–13, 415.
  treadmills, 178, 366, 422.
  windmills, q.v.
  winnowing-mill, 14.
Milling flour, 15–19.
Mill-stones, 15–16, 18, 328.
Millwrights, 100–1, 107–8, 111, 114, 345.
Mineralogy: treatise on, 28.
Mining, 27–8, 342.
  German pre-eminence in sixteenth century, 678.
  legal aspects, 30.
  mining-shafts, 30.
  regulations for miners, 30.
  see also Coal.
Mints:
  at Cassel, 343.
  at Paris, 47, 60.
  at Rome, 341.
  English, 46.
  French, 384.
  Scottish, 341.
  see also Presses.
Mirrors, 29, 228, 230, 232, 237–8.
  metallic, 40–1, 236.
  as solar furnaces, 55.
  for surveying, 537, 555.
Mixers, 327.
Mockadoes, 179.
Mongol Empire:
  European travel, 523.
  printing, 378, 380.
Moon, *and* calendar, 558–75, 577–81.
  lunar distances, 552.
Moulds:
  assaying, 60–1.
  casting metal, 39, 43–5, 47, 53.
  in paper making, 412–13, 415.
  in printing, 385, 387, 391–3, 402.
Museums:
  Alton, Hampshire, Curtis Museum, 116.
  Antwerp, Plantin–Moretus, 401 n.
  Athens, National Museum, 618.
  Greenwich, National Maritime Museum, 497.
  Leiden, Museum for the History of Science, 663.
  Munich, National Museum, 598.
  Paris, Hôtel des Monnaies, 340.
  Reading, Museum of English Rural Life, 149 n.
  Stockholm, city museum, 224.
  Swedish Commission on Mines, Museum of, 342.
  Victoria and Albert Museum, 186.
  cross-bows in museums, 353.
Music, metallic origin of, 58 n 1.
  printing of music, 405–6, 409–10.
Muslims:
  dials, 596, 600.
  globes, 612–13.

Nail making, 32, 342.
'Napier's bones' or 'rods', 627, 636.
Navigation, 523–8, 544–53.
  charts, 510, 517, 526, 536, 544, 548, 550–1, 555–7.
  chronometers, 662, 672.
  instructions, 526, 547.
  instruments, 523, 526, 546, 549, 555–7, 627.
  logs, 549–50.
  Marteloio, Italian method, 526.
  pilots, 547–9.
  tables, 526–7.
Needles:
  etching, 407.
  knitting, 183–5.
  magnetic, 518, 540–1, 523, 548–9.
  see also Compasses, magnetic.
Netherlands:
  agriculture, 13–14.
  canals and river navigation, 439, 441, 443–4, 450.
  diet, 23.
  glass, 216, 220.
  land drainage and reclamation, 300–10, 315, 318–22.
  printing, 406–7.

Netherlands (*cont.*):
  revolt against Spaniards (1566–1609), 349.
  windmills, 93, 95–7, 99–102, 106–7.
  see also Low Countries.
Netting, 181–2.
'New Atlantis', of Francis Bacon, 718.
Nickel, 30.
Niello, 48, 406.
Nocturlabes or nocturnals, 546, 614–15, 625.
Nogg *or* Moot, 119.
Nuts (metal), 339.

Observatories, 584, 639, 642.
  clocks, 665, 667, 671.
  instruments, 586–94, 625, 642.
Octant, 555–6, 636.
Oil:
  linseed, 381, 697.
  'Oil of Petre' or 'British Oil,' 687–8.
  oil-varnish inks, 405, 408.
  painting, 242.
  production, 5, 12, 687–8.
  for soap, 703–5.
Olympiads, 570, 572, 578.
Olympic games, 569, 572.
'Optics', of Alhazen, 230.
  of Ptolemy, 230.
Ores, assaying of, 62–4.
Orphreys, 196, 200, plate 12 C.
Orpiment, 29.
Orrery, 616, 618, 638, plate 27 B.
Oxen, 148.
Oxidation, 49.
Oxide, 29, 218–19, 234, 237, 241.
Oxygen, 42.

Pack-horses, 139, 141–2, 417.
  loads carried by, 438.
Paint, gold, 49.
  varnish, 381, 405, 687, 695–6.
  see also Colours.
Paintings: reproductions of, 408.
Paper and paper-making, 383, 389, 403–4, 411–16.
  'deckle', 413, 415.
  factories, 382.
  Foudrinier machine, 411, 416.
  'Hollander', 412, 415.
  introduction into Europe, 378.
  manufacturing techniques, 411–16.
  materials for pulp, 411, 415.
  paper money, 379–80.
  sizing, 415.
  stamping-mill, 412–13, 415.
  wallpaper, 415.
  watermark, 413–14.
Papyrus Carlsberg 9 (*c* A.D. 144), Egyptian mathematical astronomical text, 563.
Paston letters, *and* ships, 477.
Patterns, 182, 186–7.
  see also figured fabrics, *under* Textiles.
Pendulum, 267, 344–5, 553.
  see also Clocks.
Persia:
  architecture, 245.
  figured-silk weaving, 193, 195.
  trade routes, 380.
Pewter, 20, 29–30, 42–4, 68, 386, 393, 408–10, 679, 690–1, 695.
Pile-driving and piles, 420–7.
Pincers, 110–11, 113, 120, 212.
Pins, 354, 359.
  banking-pins in clocks, 657.
Pipes, 330–4, 363.
  made from hollow tree-trunks, 329, 330–2.
Pirotechnia of Vanoccio Biringuccio, 27, 210, 214–15, 364.
Pistons, 330–2.
Pitch, 679, 685.
Planes, 111, 113, 115, 118.
  trenching-plane, 121.
Plane-table, 540–2, 553, 556.
Planetary calculations, 614–18.
  nocturnals, 546, 614–15, 625.
Planetary models, 615.
  albion, 617.
  equatorium, 616–18.
  orreries, 616.
Planispherium of Ptolemy, 603, 605–6.
Plants: *Bixa orellana*, 694.
  Brassica napus, 5.
  Cannabis sativa L, 158.
  Carthamus tinctorius, 694.
  Chlorophora tinctoria, 694.
  Curcuma, 694.
  Dioscorea, 2.
  Fagopyrum esculentum, 5.
  Genista tinctoria, 694.
  Gossypium, five species, 159.
  Guaiacum (lignum vitae), 672.
  Helianthus tuberosus, 2.
  Ipomoea batatas, 2–3.
  Isatis tinctoria, 693.
  Lecanora, 694.
  Nicotiana, 8–9.
  Reseda luteola L, 694.
  Rhamnus catharticus L, 692.
  Rhus vernicifera, 696.
  Rubia tinctoria, 693.
  Solanum andigenum, 1–2.
  Solanum tuberosum, 2.
Plates and dishes, metal, 343.
  'plates' for illustrations, 409.
Playing-cards, 380–1, 385.
  'Master of the Playing Cards', 406.
Plinth, 587–9, 599.
Plumb-lines, 512, 526, 538, 541, 582–3, 588, 590, 593, 598–9, 608.

Polder, *see* Drainage.
Polimetrum, surveying instrument, 538, 541.
Polishing of engraving plates, 408.
  lenses, 233–7.
  metal, 343, 350.
  speculum-metal, 40–1, 237.
Portugal:
  adoption of Gregorian calendar, 579.
  cartography and navigation, 530, 544, 547–8
  ships, 476–8, 480–1.
  snuff, 10.
  tobacco, 8.
Potash, 206–7, 222, 229, 685, 700.
  potash-lime crystal, 221–2.
Potassium carbonate, 63, 206.
  nitrite, 63.
Potato, *see* Food.
Pottery, table-ware, 20.
Power-operation of machinery, 18–19, 158, 162, 167–9, 239, 324, 330, 340–1.
  see also Horse-power, Water-power, Windmills.
Press, printing-house; Blaeuw, P. and J., 402.
  Clarendon Press, Oxford, 402.
  Imprimerie Royale, 402.
  Plantin and Moretus, 401–2.
  Ripoli, 393.
  Stamperia Vaticana, 402.
Presses:
  balance-press, 340–1.
  coinage, 338–40.
  linen-press, 177, 382, 389, 397.
  printing, 382, 389–90, 396–401, 408–9.
  screw-press, 41, 177, 334, 337–9, 382, 414.
Pressure:
  air-pressure, 324.
  water-pressure, 324.
Prices, sixteenth century rise in, 30.
Prime movers, 325, 328, 330, 340.
'Prince Rupert's metal', 37.
Printing, 43–4, 337, 676.
  block-printing, 379–381, 404–5, plate 2 B.
  'chase', 396–7.
  compositor's work, 388–91, 394–6, 403.
  die-casting, 385.
  early typefounding, 383–6.
  ink, 381–2, 390, 398, 403–8, 415.
  intaglio printing of illustrations, 379, 406–10.
  invention of printing, 377–8.
  manuals on printing, 385, 391.
  metals, 385–6, 392–3, 406.
  moulds, 385, 387, 391–3, 402.
  music printing, 405–6, 409–10.
  presses, 382, 389–90, 396–401, 408–9.
  rates of production, 387–8, 393, 404.
  readers, 389, 403.
  relief printing, 379–80.
  techniques, outside Europe, 378–80.
Printing (*cont*,):
  1462–1730, 390–401; eighteenth century, 401–4.
  tools and equipment, 386–8, 391–2, 394, 398–9, 402–7.
  workers, 386–7, 389–90, 395, 402–3.
  working of fifteenth-century printing-office, 386–90, 395.
Prints:
  Brussels 'Virgin', 380.
  Buxheim 'St Christopher', 380, plate 2 B.
Probierbüchlein ('Essay on Assaying'), 27, 59, 63.
Projectiles:
  bombs, 38, 347, 368–9, 374.
  cannon-balls, 362, 368, 374.
  grenades, 347, 369.
  musket-balls, 34.
  scientific principles, 374–5.
  shot, 357, 359–61, 368, 375.
  stones, 353.
Protractors, 593, 623.
Prussia:
  diet, 2.
  windmills, 97.
  for canals, *see* Germany.
Pulleys, 334, 337, 432.
Pumps and pumping: for bridge-building, 420, 422–3, 425–6.
  chain, 484.
  chain-and-bucket, 325–7.
  drainage, 307–8.
  force-pumps, 333.
  hand-pump, 484.
  pneumatic, 636–8.
  steam injector, 52.
  suction, 324, 329–33, 344, 432.
  vacuum pump, 637, plate 27 A.
Punches, 341, 385–7, 391–2, 402, 405, 410.

Quadrant, 362, 374–5, 522, 526, 528, 536–7, 544–6, 555–6, 586, 588, 597–600, 608, 614–15, 625, 636, 640–1.
Quicklime, 29.

Rakes, 134, 137.
Ratine, 179.
Realgar, 29.
Reamer, 111.
Reapers, mechanical, 136.
Rectangulus, 593–4.
Reels, 162.
Refining, of sugar, 7–8.
Refractory materials, 39.
Religious houses, and drainage works, 309, 316, 318.
  prints, 380.
Renaissance, effects of the, 151, 378.
  and precision instruments, 609.

Resin, 685.
Rhymes and maxims for apprentices, 112–13.
River navigation, 440, 450, 456–60, 464–5.
  research on flow of rivers, 464.
Rivets, 354.
Roads and streets:
  ancient, 269–71.
  Germany to Rome, end of fifteenth century, 534.
  Hellenic, 272–5.
  London, 283, 296–8.
  medieval, 282–4.
  Renaissance, 285–93.
  Roman, 276, 279–82, 504.
  — in Britain, 277–8.
  'Street called Straight', Damascus, 275.
  street lighting, 282.
Rolls for working metals, 340–3.
Roma Instaurata (1444–6) by Flavio Biondo, 288.
Romans:
  bridges, 417–18, 420, 432.
  calendar and chronology, 575–8.
  canals and river navigation, 439.
  dials, 596–8, 600.
  maps, 502–4, 507–10, 518.
  pavements, 194.
  reckoning-apparatus, 501–2.
  roads, 276–82, 504.
  surveys, 502, 504, 511.
Roofing-sheets, 343.
Rope-tackle, 107–8, 139.
Rotary fan, 20–1.
Routers, coach-makers', 113, 115.
Royal Navy, 477–8, 481, 679.
Royal Observatory, 552, 557.
Royal Society, 15, 41, 58–9, 358, 374, 436, 486, 556, 630, 681, 685, 703, 717.
  'Philosophical Transactions', 22, 682.
Russia:
  adoption of Gregorian calendar, 579.
  flax, 156.
  hemp, 158.
  potash or pearl-ash, 229.
  tobacco, 8.
  trade-routes, 380.
  windmills, 89, 92–3, 98–9, 103, 106.

Sal alkali, 210.
Sal ammoniac, 48, 225, 689, 706.
Salt:
  salt-pans, 76.
  salt-works, 82.
Saltpetre, 39, 41, 62–3, 355 n 2, 695, 706.
Sand-glass, 526, 550.
Sandiver, 62 and n, 63.
Sanitation, 273, 282–3.
Satin, 192, 199–200, 203, 205.
Saws, 110, 365.
  bow-saw, 112.
Say, 179.
Schedula diversarum artium, of Theophilus Presbyter, 206.
Science, impact on technology, 56, 230, 258, 679–83, 706, 716–19.
  assaying, 59.
  bridge-building, 432.
  engineering, 344–5.
  hydraulics, 313–15.
  instruments, 620–1.
  metals and alloys, 56–7, 68.
  quantitative analysis, 59.
  ships, 482.
  strength of materials, 58–9, 250–1, 432.
  structure of matter, 56–7.
  town-planning, 285–8.
  war, 373–5.
Scientific theories:
  atomism, 56–7.
  parallelogram of forces, 432.
  phlogiston theory, 57, 719.
  theory of dimensions, 432.
  theory of the arch, 433–4.
  vacuum, *q.v.*
Scotland:
  agriculture, 3, 142.
  alcoholic spirits, 11.
  coinage, 341.
  date of New Year's Day, 580.
  diet, 3.
  farm-vehicles, 142–4.
  flax, 157–8.
  Highlands mapped, 554.
  linen, 151, 176.
  ships, 478.
  soap, 703.
  spinning-wheels, 151.
  textile industry, 163.
  windows, 237.
  wool, 152.
Screws, 113–14, 116, 326, 334–9, 343, 345, 382, 398–400.
  advances in sixteenth and seventeenth centuries, 325.
  Archimedean screw, 106, 304–5, 423.
  'Barrow' screw regulator, 667.
  in clocks, 657, 659.
  lead-screw, 335–6.
  micrometer screw, 554.
  screw-cutting, 334.
  screw-presses, 41, 177, 334, 337–9, 382, 414.
  threaded screw, 629.
Scythes, 136–8.
Seasons, cycle of, 559–60, 569, 573.
Sector, 627–8, 636.
Serge, 178–9.

Sextant, 556–7, 639.
Shafts, 328, 334.
Shag, 179.
Shalloon, 179.
Shearing-machines, 173–5.
Shears, 340, 352.
Sheffield plate, 48.
Ships and ship-building, 432, 486–93, 495.
  bells, 484.
  decoration, 493–5, 498.
  developments in seventeenth century, 482–6; from 1700–50, 495–9.
  docks, 492.
  guns, 473, 478–81, 499.
  models, 482, 490–2, 497, plate 24.
  mould-loft, 489–90.
  oars, 471–3.
  rigging, 476–7, 483, 485–7, 495–7.
  rudder, 475–6.
  rust prevention, 679.
  sails, 472, 474–7, 481, 485–7.
  shipyards, 486.
  steering-wheel, 497–8.
  stores, 487.
  textbooks, 482, 488.
  timber, 487–9, 481, 492–3.
  tonnage, 480–1, 493.
  types, Armada campaign ships, 480–2; barges, 478–9; brigantine, 491, 499; caravels, 476–8; carracks, 475–9; cogs, 476; East India Co. ships, 481, 496; frigates, 496; full-rigged ships, 474–8, 499; frigates, 496; full-rigged ships, 474–8; galleasses, 473, 478–80, plate 21 B; galleons, 479–81, 483, 487; galleys, 353, 471–4, 478–80; herring-busses, 499; hoys, 498; pinks, 485; pinnaces, 478–9; round-ships, 473–4, 479–80; sloops, 491; snows, 499; trading-ships, 472–8, 481–2, 496, 498–9; warships, 471–4, 478–82, 497, 499; whaling-ships, 497; yachts, 486, 497–8.
Ships, named:
  Antelope, 479.
  Ark Royal, 481.
  Bull, 479.
  Charles, 491.
  Cordelière, 478.
  George (1546), 478.
  Golden Hind, 477, 494.
  Great Michael (1506), 478.
  Hart, 479.
  Henry Grâce à Dieu (Great Harry, Harry, Harry Grâce à Dieu, Henry Imperial, Imperial Carrack, Great Carrack), 478, 487, plate 21 A.
  Madre de Dios, 481.
  Nina, 477.
  Regent, 478.
Ships, named (*cont.*):
  Royal George, 499.
  Royal Prince, 485–6, 494, plate 22.
  San Juan, 480.
  San Martin, 480–1.
  São João, 480.
  Shark sloop, 491.
  Sovereign of the Seas, 482, 485–6, 494, plate 23.
  Subtile, 479.
  Tiger, 479.
  Victoria (1518), 477.
  Victory, 499.
Shuttles, 161, 165–70, 187.
Sickles, 134, 136–7.
Sieves, 16–18.
Sighting-tubes, 375, 593–5.
Silica, 206, 218.
Silk, 151, 165, 178.
  Chinese, 195, 201–2.
  Islamic, 191, 197, 199.
  Italian, 165, 196, 199, 203.
  medieval, 190–1, 196–8, 200, 202.
  raw silk trade, 195.
  sericulture, 195.
Silver, 27, 29, 33, 38, 40–2, 47–8, 53, 82–3, 342.
  assaying, 59, 63–8.
  blanching, 56.
  chloride of silver, 241.
  ground, 49.
  tape, 48.
Sledges, 140–1.
Slide-car, 141.
Slide-rule, 628.
Sluices, 441–2, 444, 454, 462.
  'portcullis' sluice, 441–2.
Smalt, 678, 698.
Smelting, 27, 28, 29, 30, 31–3, 51, 74, 79.
Smiths, 116.
  anchor-smiths, 116.
  blacksmiths, 111–14, 116, 126–7, 487.
  blade-smiths, 343.
  chain-smiths, 116.
  goldsmiths, 623.
  nail-smiths, 116.
  shear-smiths, 116.
  sword-smiths, 115, 350.
  tinsmiths, 116.
Snuff, 10.
Soap, 169–71, 175.
  soap making, 703–5.
Soda, 685, 700, 703.
Sodium carbonate, 206.
  oxide, 234.
Soldering, 55.
Solders, 42, 48.
Spades and shovels, 115, 134–6, 138.
Spain:
  adoption of Gregorian Calendar, 579.

Spain (*cont.*):
  cannon, 367.
  chemistry, 677.
  coinage, 341.
  damasks, 201–2.
  diet, 1–3.
  dyeing industry, 695.
  figured silks, 196, 198–9.
  infantry, 348.
  knitting, 185.
  medieval looms, 192.
  navigation, 526, 548.
  paper-making, 412.
  satin, 200.
  ships, 477–8, 480–1, 499.
  soap, 703, 705.
  textile industry, 151.
  tobacco, 8.
  windmills, 89, 95–6, 106.
  wool, 152, 155.
Spanners, 112, 114, 338.
Spectacles, 229–31, 630–1, 633, 699, plate 1.
Speculum-metal, 38, 40–1, 237.
Spelter, *see* Pewter.
Spindles, 160, 162–3, 223–4.
Spinning, 151, 153, 160–2.
Spinning-wheels, 151, 160–2.
Spits, 20–1.
Spoons, 20.
Sprang, 181–3, plate 8 B.
Springs, balance-spring, 344.
Squares, geometric, 608.
  shadow-square, 608.
Stament, 179.
Stars, in navigation, 521, 523, 545–7, 552–4, 556.
State intervention:
  control of arms and ammunition manufacture, 347, 352, 361.
  in metal industries, 30.
Statics, 433.
Statues, casting of, 38–9.
Steam-power, 52, 83–4, 687.
  steam-engine, 83–4, 330, 344, 368.
Steel, 28–9, 31, 33–4, 57, 115, 338, 343.
  crucible-cast, 35.
  hardening process, 34–7.
  heat treatment, 35.
  quenching, 35–6.
  techniques, 32–3, 79.
  temper-colours, 36.
  tool used in engraving, 407.
  weapons, 350.
Stibnite, 29.
Stone:
  cannon-balls, 34.
  stone-masonry in bridges, 419–20, 423–4, 426, 428, 436; in canal-building, 446, 450, 453, 455, 462, 468.
Straw, used in paper-making, 411, 415.
Stuff, 179.
Sulphides, 48, 65, 221, 406.
Sulphur, 42, 48, 221.
Sun, 506, 513, 517, 521, 523, 545, 547, 549, 551–3, 556.
  and calendar, 558, 560, 567, 577.
Sun-dials, 586, 594.
  altitude dial, 594–600.
  direction dial, 600.
  equatorial dial, 598.
  'ham' dial, 596–7.
  pocket or portable dial, 533, 535, 594, 598, 626.
  Saxon scratch-dial, 594.
  'shepherd's dial' or 'chilindre', 596.
  ship-dials, 597–8.
  skaphe or hemicycle, 594, 596.
  universal rectilinear dials, 597–8.
Surveying and surveys, 317, 320, 373, 504, 510–15, 537–44, 554–5.
  French geodetic survey, eighteenth century, 554.
  instruments, 510–13, 528, 537–43, 555, 609–12, 627–8.
  levelling, 542–3.
  Ordnance Survey instituted (1791), 554.
  see also Triangulation.
Sweden:
  adoption of Gregorian calendar, 579.
  canals and river navigation, 455.
  chemistry, 682.
  flax, 156.
  glass, 217.
  iron industry, 31, 79, 342–4.
  tinplate, 689.
  traditional weaves, 187.
  windmills, 97, 99.
Switzerland:
  bridges, 427–8.
  clock-making, 674.
  pikemen, 348–9.
  stained-glass windows, 241.
  weaving, 159.
Swords, 35, 350–1.

Tabby, 187–8, 194–5, 197–205.
Tables:
  Alfonsine, 535, 585, 617.
  amplitude, 549.
  astronomical, 503, 547, 557, 584–5.
  conversion, 536.
  gravities, 22.
  logarithm, 553.
  lunar, 552, 557.
  mathematical, 57–8, 521, 541–2.
  nautical, 552–3, 557.
  navigation, 526–7.
  Peutinger table, 503–4, 514–15.

Tables (*cont.*):
  range, 361, 369, 374.
  shadow-lengths, 595.
  stellar (Flamsteed's), 667.
  tide, 553.
  trigonometrical, 542, 551.
  see also Ephemerides.
Taffeta, 179.
Tamis, 179.
Tammies (worsted), 178–9.
Tapestry, 193–4.
Tappets, 328, 412.
Tar, 685.
Tartar, 41.
  from wine casks, 217, 218 n.
  white, 29.
Tea, *see* Drink.
Teazels, 172.
Telescopes, 41, 231–4, 237, 552, 554–5, 630–6, 640–1.
  in surveying instruments, 543, 555.
Temperature-control, 33, 36, 64, 210, 238, 680, 687.
  compensation in clocks and watches, 672–3.
Textiles, 151, 681.
  fibres, cotton, 159–60; flax, 156–8; hemp, 158–9; wool, 152–6, figured fabrics, 187–205, plates 10–15.
  fustian, 159.
  machinery, 152–5, 157–62, 164–70, 172–8.
  patterns, 164–6.
  processes, bleaching, 174–6, plate 31; calendering, 177–8; carding, 153–4; combing, 154–6; finishing, 169–78; fulling, 169–72; pressing, 176–8; raising, cropping, and frizing, 172–5; reeling, warping, dressing, 162–4; shearing, 173–5; spinning, 151, 153, 160–2; washing and scouring, 153, 162–3, 169, 171; weaving, 164–9, 182–205.
  see also names of separate fibres and fabrics.
Thermometers, 630, 636–7, 680.
Theodolite, 538, 541–3, 553, 609–11, 627, 636.
Timber:
  in bridge-making, 423, 425, 427.
  in building, 248–50, 253–7, 262–6.
  in canal construction, 447, 450–1, 453, 455, 463.
  in iron industry, 31.
  in ship-building, 487–9, 481, 492–3.
  see also Wood.
Tin, 27, 29, 34, 38, 40–2, 49, 342, 363, 689–90.
  alloys, 42–3, 55, 58.
  assaying of tin ores, 62.
  tin wares, 343.
  see also Tinplate.
Tincal, 228 and n.
'Tinglass', 43.
Tinplate, 343, 689–91.
Tires, 114, 127, 128.
Tire-bender, wheelwright's, 113, 127.
Tissued fabrics, 196–200.
Tobacco, 1, 8–10.
Tongs, 34, 113, 210, 341.
  weeding-tongs, 134–6.
Tools:
  catalogues and lists, 116–18, 122–3.
  cutting-tools, 336.
  hand-tools, 110, 334.
  home-made, 112–13.
  machine-tools, 345, 375.
  mass-produced, 113–14.
  metal, 19, 37.
  specialization, 116–17.
  tool-making, 334–5; tool-making centres, 115.
  wooden, 114–15.
  used in agriculture, 14–15, 34, 112, 115, 134–9; bridge-building, 420; cannon manufacture, 365; coach-making, 113, 115; coinage, 341; cooking, 20; cutting stone, 35–6; distilling, 11–12; engraving, 407–8, 624; food disintegrating techniques, 16–19; glass-making, 208, 210–12; 217, 219–20, 222–9, 231–2, 234–6; making machines, 334–7; printing, 386–8, 391–2, 394, 398–9, 402–7; sugar refining, 7–8; testing spirits, 22.
Torquetum (or 'turketum'), 585, 592–3, 627.
Torricellian tube, 543.
'Tortoise-shell', 696.
Touchstone, assay by, 65–6.
Town-planning, 269–98:
  ancient, 269–72.
  Hellenic and Hellenistic, 272–5.
  medieval, 282–5.
  Renaissance, 285–93.
  Roman, 275–82.
  satellite towns, 285–6.
  treatises on town-planning, 285–6, 288, 290.
  towns described:
    Alexandria, 275; Amsterdam, 293–5; Antioch, 275, 282; Aosta, 280; Athens, 272–3; Babylon, 270–1; Byzantium, 279; Carcassonne, 283; Charleville, 290; Constantinople, 275; Corinth, 275; Damascus, 275; Delos, 274; Dura Europus, 275; Ephesus, 275, 282; Florence, 280; Harappa, Indus Valley, 270; Henrichemont, 291; Hull, 284; Kahun, Egypt, 269–70; Leghorn, 287; London, Roman, 278–9; London, seventeenth century, 295–8; Lucca, 280; Marzabotto, 276; Miletos, 272–3; Mohenjo-Daro, Indus Valley, 270; Monpazier, 282–3; Neubrandenburg, 285; Olynthos, 273–4; Ostia, 280–1;

Town-planning (*cont.*):
  towns described (*cont.*):
    Palma Nuova, Venetia, 286; Palmyra, 280; Paris, 293; Piraeus, 271–2; Pompeii, 274–5; Priene near Miletos, 273–4; Richelieu, 291–3; Rome, 276, 281–2, 287–9; Selinus, Sicily, 273; Silchester, 277; Timgad, Algeria, 280, 282; Turin, 280, 286–7; Ur, 271; Verulamium, 276–8; Vitry-le-François, 289–90; Winchelsea, 282.
Toxophilus (1545) by Roger Ascham, 351.
Trade:
  specialization of trades, 116.
  trade cards, 225, 623, 634.
Transport:
  by land, 84–5.
  by rail, 84.
  by sea, 19.
  by water, 84.
  comparison of loads, 438.
  cost, 438.
  horse-drawn railways, 85.
  of coal, 84–6.
  of grain, 19.
  tilting-rails, 85.
  see also Canals, Roads, River navigation, Vehicles.
Treadles, 160–1, 223–4, 237.
Triangulation, 503, 511, 517, 539–40, 544, 554, 556, 626.
Trigonometria, 626–7.
Trigonometry, 503, 526, 542.
  tables, 542, 551.
  trigonometrical calculators, 614–15.
Tripoli powder, 237.
Triquetrum *or* Ptolemy's rulers, 589–90.
Trompe, 52–3.
Trowels, 117.
Tubes, for optical instruments, 634–5.
Tunnels, 467.
Turbines, 329.
Turnips, cultivation of, 15.
Turpentine, 687.
Tweezers, 394.
Twill, 188, 195–6, 198–9.
Type-metal, 29, 43–4.

United States of America:
  windmills, 89, 95, 106.

Vacuum, 324, 332, 344, 432.
  vacuum pump, 637, plate 27 A.
Valves, 330–2.
Varnishes and varnishing, 687, 695–6.
Vats:
  gravity-fed, 412.
  for paper pulp, 412–13.
Vehicles:
  barges, 438–9.
  carts and wagons, 111, 142–7.
  coaches, tools for, 113, 115.
  on farms, 134, 139–48.
  load capacity, 438.
  tumbrils, 143–4.
  wains, 144.
Velvet, 164, 179, 199, 203–5, plate 15 C.
Ventilators, 30.
'Verulamium plan' for advancement of industry, 680–1.
Vices, 110, 114, 337–8.
  watchmaker's pin-vice, 120.
Voile, 179.

Wales:
  bridges, 434–6.
  farm vehicles, 140, 144.
  iron industry, 31.
  lacquer manufacture, 688.
  wool, 152.
Walls:
  of buildings, 247, 261, 266–7.
  of towns, 270–1, 278, 280–7, 291. *see also* Fortifications.
  papering of walls, 415.
Warfare:
  administration and logistics, 347–8.
  art of war, 347–50.
  military forces, 347–9.
  naval wars, 350–68.
  strategy and tactics, 348–9.
  in relation to iron industry, 31; power of the State, 348; medicine and surgery, 373–4; science and mathematics, 371–5; scientific instruments, 622; water engineering, 318.
Wars:
  English Civil War (1642–9), 369.
  Hundred Years War between English and French, 349.
  Italian wars of the sixteenth century, 349.
  Religious wars (*c* 1540–1648), 349.
  Thirty Years War in Germany (1618–48), 349, 622.
  Wars of the Roses, in England, 349.
Watches:
  drum-shaped, 656.
  jewelled watch-bearings, 670–1.
  'pendulum watches', 669.
  pocket-watches, 636.
  repeating-watches, 669.
  see also Clocks and watches.
Water-clocks, 568, 601–4.
Water-engineering, 275, 280, 285–6, 294.
  aqueducts, 289, 446, 466–7.
  drainage, 270, 276, 281, 291.
  irrigation, 286.

Water-engineering (*cont.*):
  sewers, 281.
  see also Canals, Dikes and dams, Drainage and reclamation of land.
Water-level, 511–12, 542–3, 609–11.
Water-power, 19, 30, 32, 45, 82–3, 162, 168, 223, 327–9, 342–3, 350, 359, 367, 412, 415.
Water-supply, 74, 274–5, 277, 280, 282.
  for London, 464.
  for Paris, 462.
Water-wheels, 15, 18, 30, 32, 169–70, 327–8, 342–3, 414, 420.
Wax, 57.
Weapons, 347–75.
  bayonets, 348.
  halberds, 351.
  lances, 348, 351.
  pikes, 348, 350–1, 353.
  swords, 35, 350–1.
  see also Artillery, Firearms, Guns.
Weaving, 164–9, 187–205.
  automatic, 168–9.
Weights, 57.
  for assaying, 61, 66–8.
Weirs, 440–1, 448–9, 456, 458, 462, 464, 467.
Whalebone, 124–5.
Wheels:
  cart-wheels, 142–4, 146–7.
  cog-wheels in clocks and watches, 654–5.
  crown wheels, 345.
  'dished' wheels, 112, 124, 146.
  fly-wheels, 223–4, 326, 423.
  gear-wheels in clocks, 641.
  knurled wheel used for mezzotints, 407.
  lantern-wheel, 18.
  making of wheels, 123–8, plate 6.
  scoop-wheels, 303–6, 321–2.
  wheel-engraving, 222–4.
  wheels used in glass-making, 210, 226, 239; in polishing armour, 351.
  see also Spinning-wheels, Water-wheels.
Winches, 97–9, 177, 441.
Wind-charts, 555.
Windlasses, 47, 367, 423, 439, 442, 483.
Windmills, 15, 18.
  automatic fantails, 98–9, 107.
  auxiliary machines, 106.
  books, 89, 96, 99, 108.
  brakes, 103–4.
  contemporary descriptions, 89, 91, 99.
  for land drainage, 303, 307–8, 317, 321–2, plate 20.
  hoists, 105.
  in textile industry, 170.
  mechanical aids, 97–8, 106.

Windmills (*cont.*):
  millstones, 104–5.
  post-mills, 89–95, 97–9, 103, 105, plates 4, 5.
  rollers, 96–7.
  roofs, 93, 97.
  rotating caps, 303.
  round-houses, 94.
  sail-cloths, 99–100.
  sails, 93–4, 96–103, 106–7.
  smock-mills, 95, 106–7.
  survivals, 89–90, 96.
  tools, 107–8.
  tower-mills, 89–90, 95–7, 99, 102, 107.
  turret windmill, 330.
  weatherboarding, 93–5.
  winches, 97–9.
  wind shafts, 102–3.
Windows, 237–42.
  lead strips, 41–2, 44.
  sashes, 267.
  stained glass, 32, 240–2.
Wind-power, 83, 412, 415.
Wind-rhumbs, 518, 524–7.
Wind-rose, 517, 523–7.
Wire:
  coiled drawn, 55.
  copper, 59.
  silver, 48, 59.
  wire used in paper-making, 413.
  wire-drawing, 32, 342, 414.
Wood:
  ashes, 206–7, 210.
  for clocks, 672.
  for coopering, 129–30.
  distillation furnace, 686.
  for machines, 326, 329, 332.
  replaced by coal, 78–81, 220–1, 685–6.
  substitutes for, 685–8.
  supplies, 77.
  for tools, 115.
  for wheels, 123, 126.
  wood-pulp for paper, 411, 415.
  wood-tar, 12.
  see also Charcoal, Timber.
Woodcuts, 404–6, plate 2 B.
Wool, 15, 151–6, 163–4, 169, 172–7, 195–7.
Workshop recipes, 27.
Wrenches, 113–14.

Zaffre, 678, 698, 702–3.
Zinc, 30 and nn 1 and 2, 37–8, 41, 43, 46, 690–2.
  oxide, 51.
  smelting, 51.

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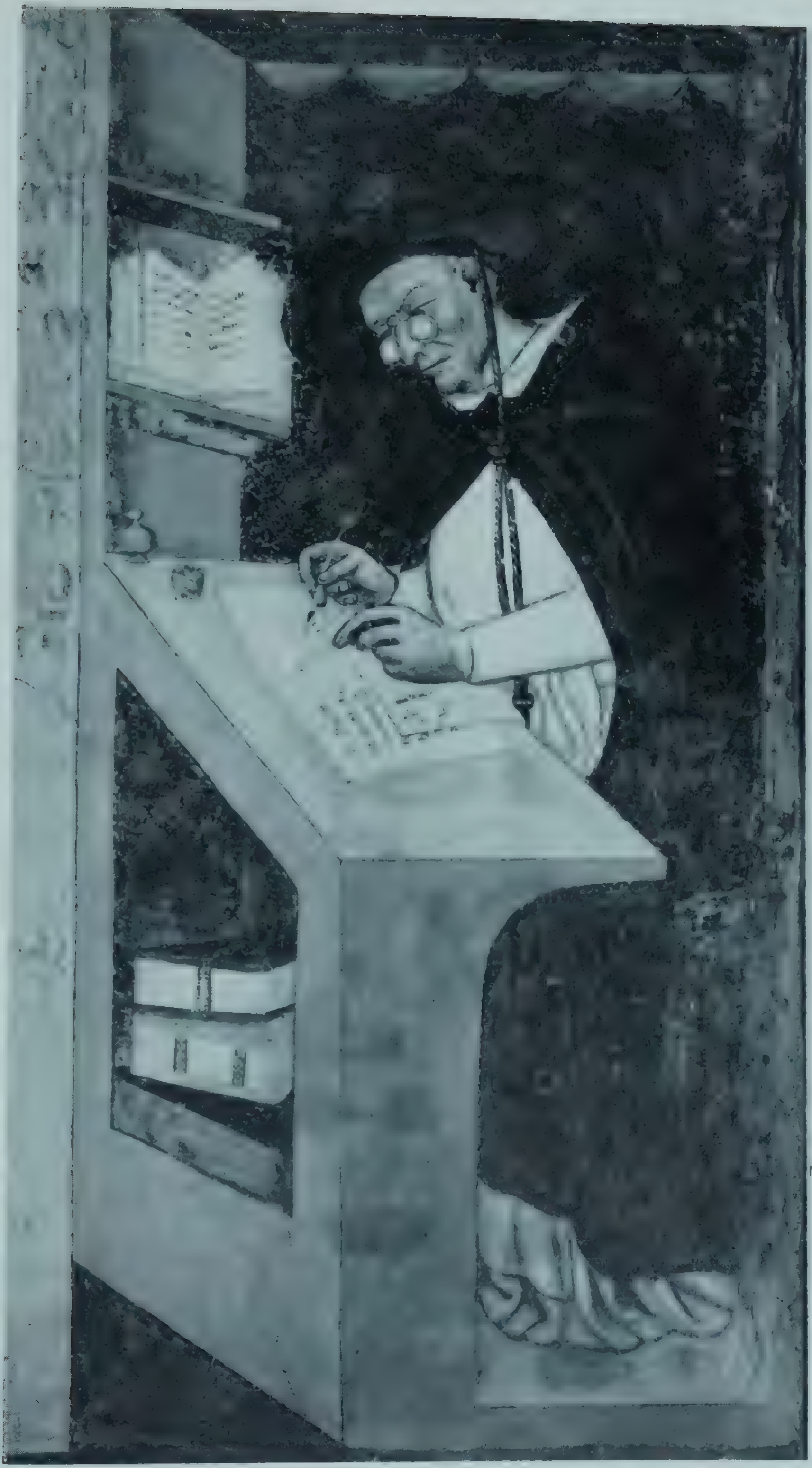
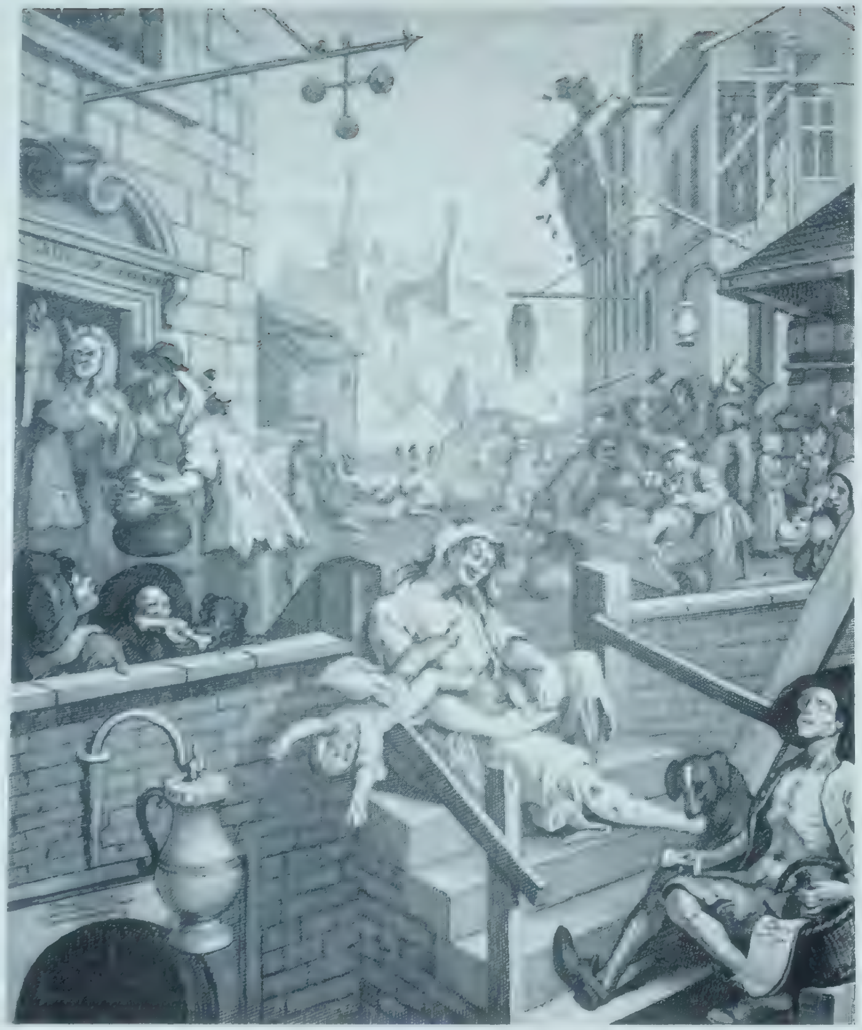
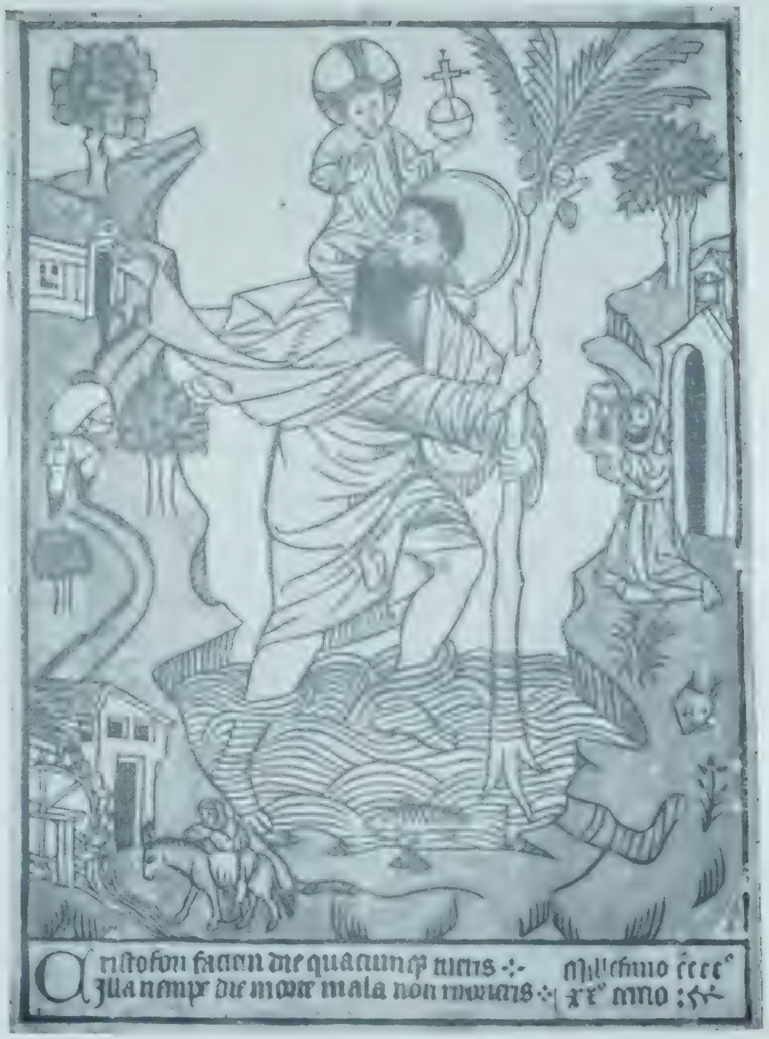


Portrait by Tommaso da Modena of a Dominican monk, probably Hugh of St-Cher, showing him wearing spectacles. From a fresco at Treviso, 1352. (p 230)

PLATE 2

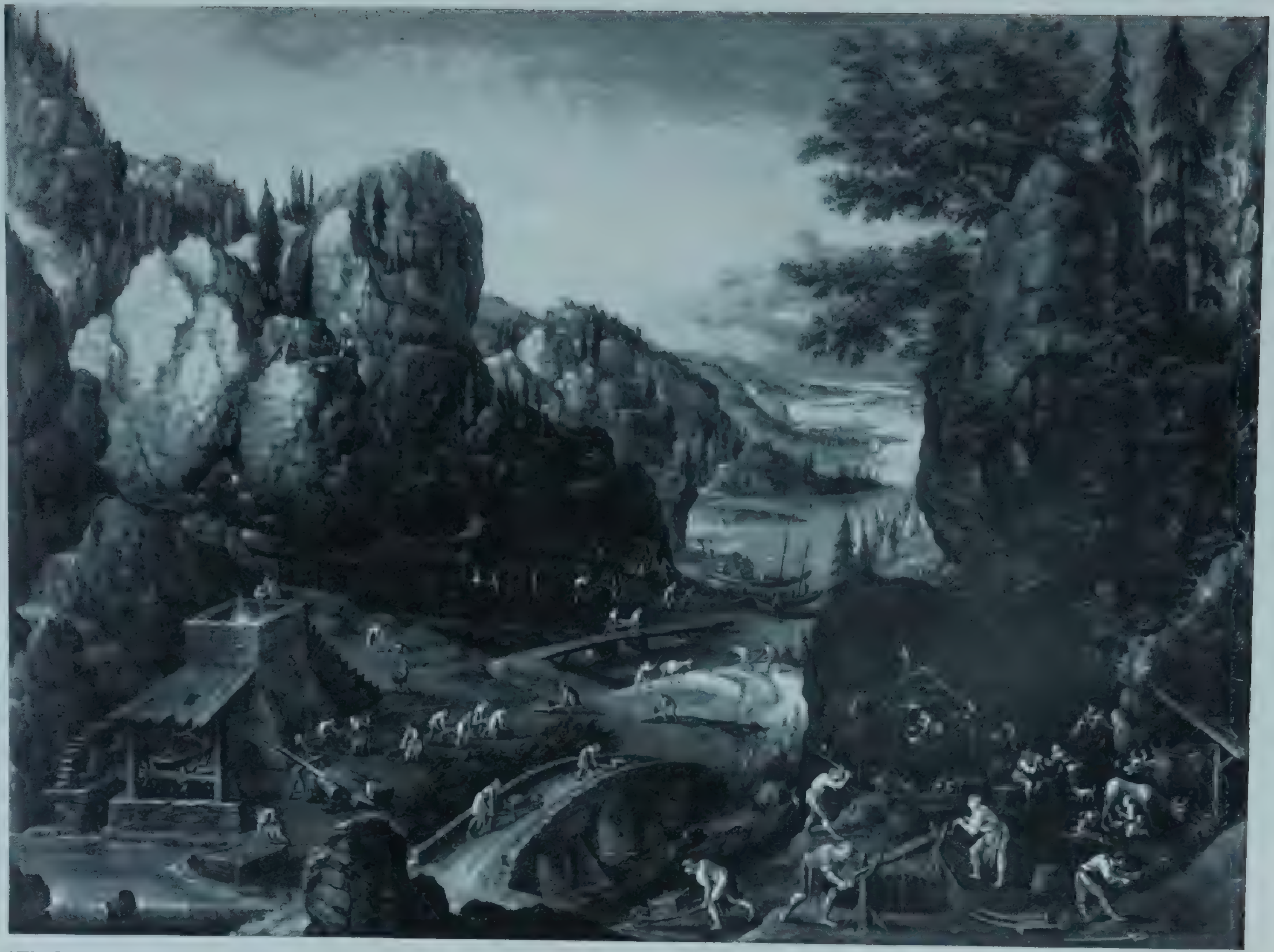


A. *'Gin Lane', an engraving of 1751 by William Hogarth (1697–1764).* (p 11)


Cristofori faciem die quacunque tueris
Illa nempe die morte mala non morieris
Millesimo cccc°
xx° tercio

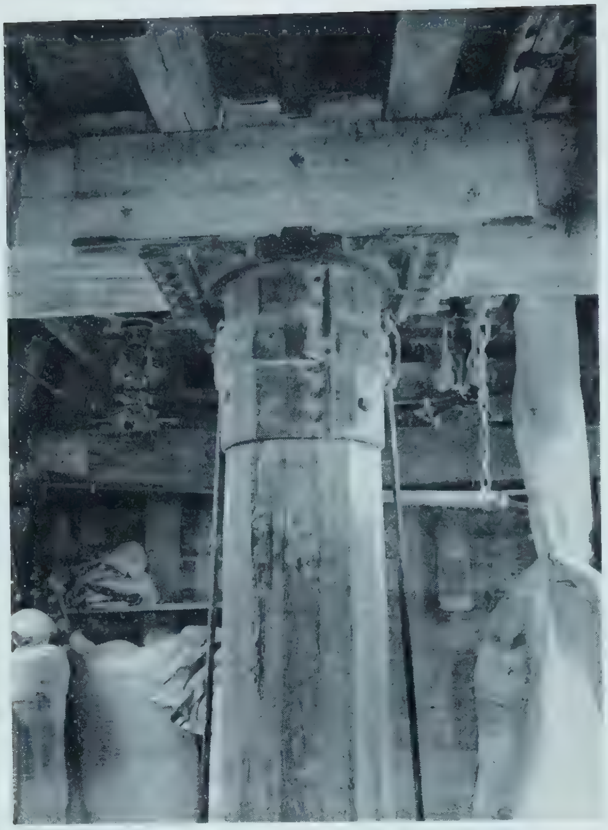
B. *The Buxheim St Christopher, 1423.* (p 380)

PLATE 3

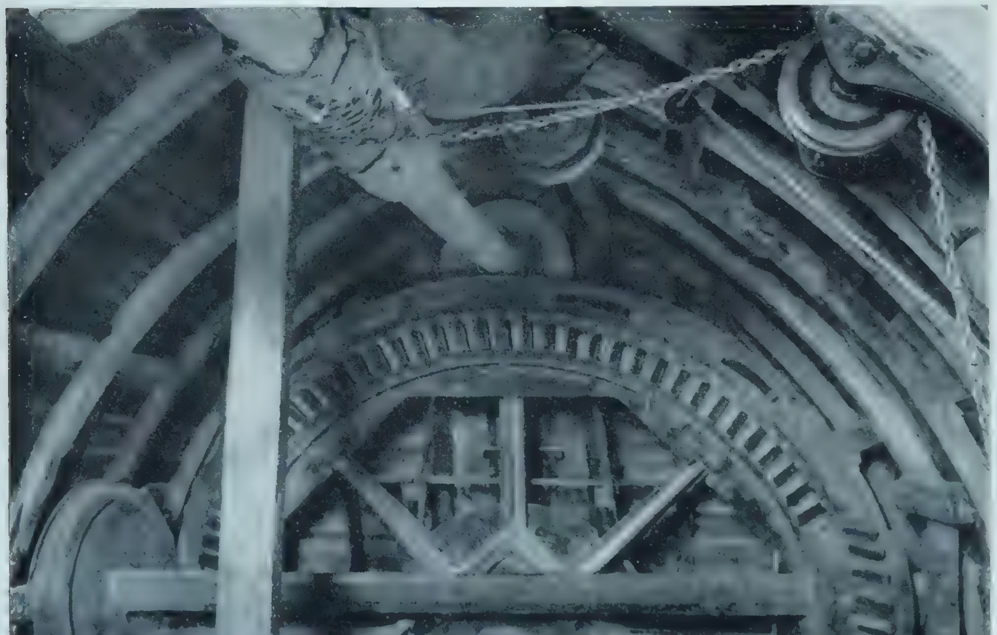


'The Iron Mountain', an oil-painting of 1606 by Martin van Valkenborch (1542–c 1610) of Malines. The picture shows (left to right) *tapping a blast-furnace (note water-driven bellows and counterpoise); forge with water-driven hammers; mouth of iron-mine, with rough windlass for raising spoil; chafery for converting cast iron into wrought iron; the 'canteen'; open-cast mining. The scene is supposed to be placed near Huy, Belgium.* (pp 30, 50, 79)

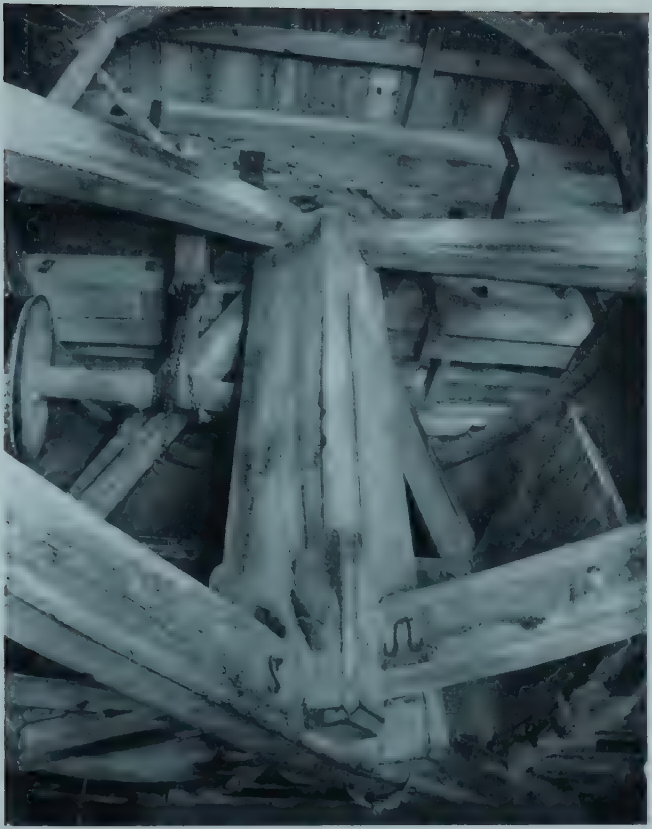
PLATE 4



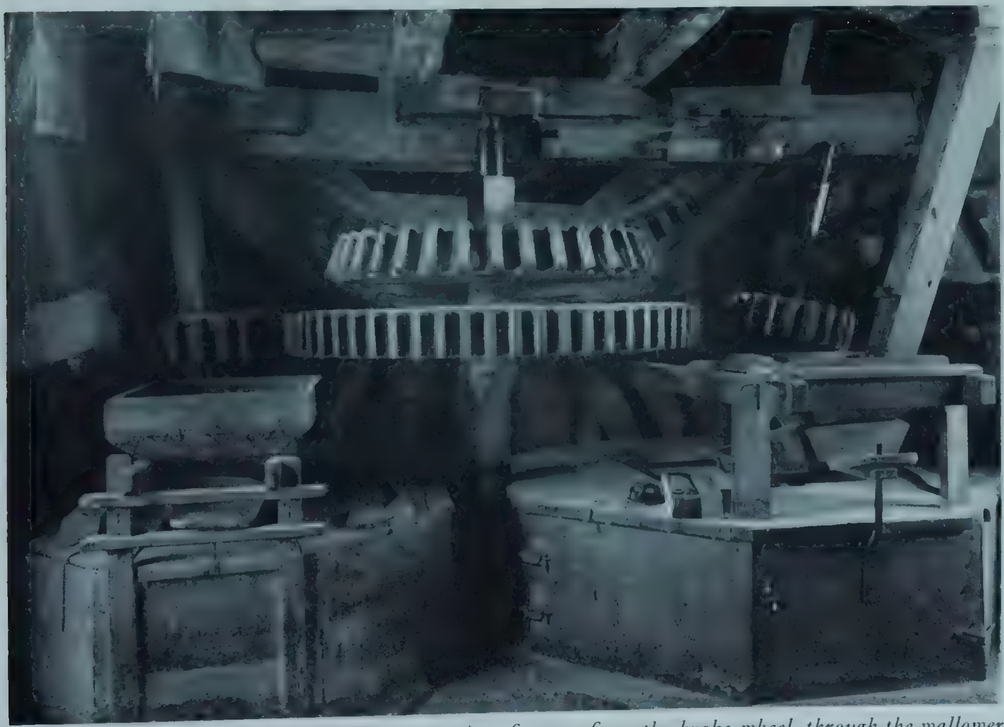
A. *Post-mill at Parham, Suffolk, showing the top of the post and the crown-tree resting on it with an iron 'samson head' bearing. Note the governors in the background.* (p 92)



B. *The same mill, showing the brake-wheel mounted on the wind-shaft. A drive for the bolter (not shown) is taken off-centre from this wheel by means of a skew pinion. The sack-hoist is driven by belt from a pulley in front of the brake-wheel.* (p 105)

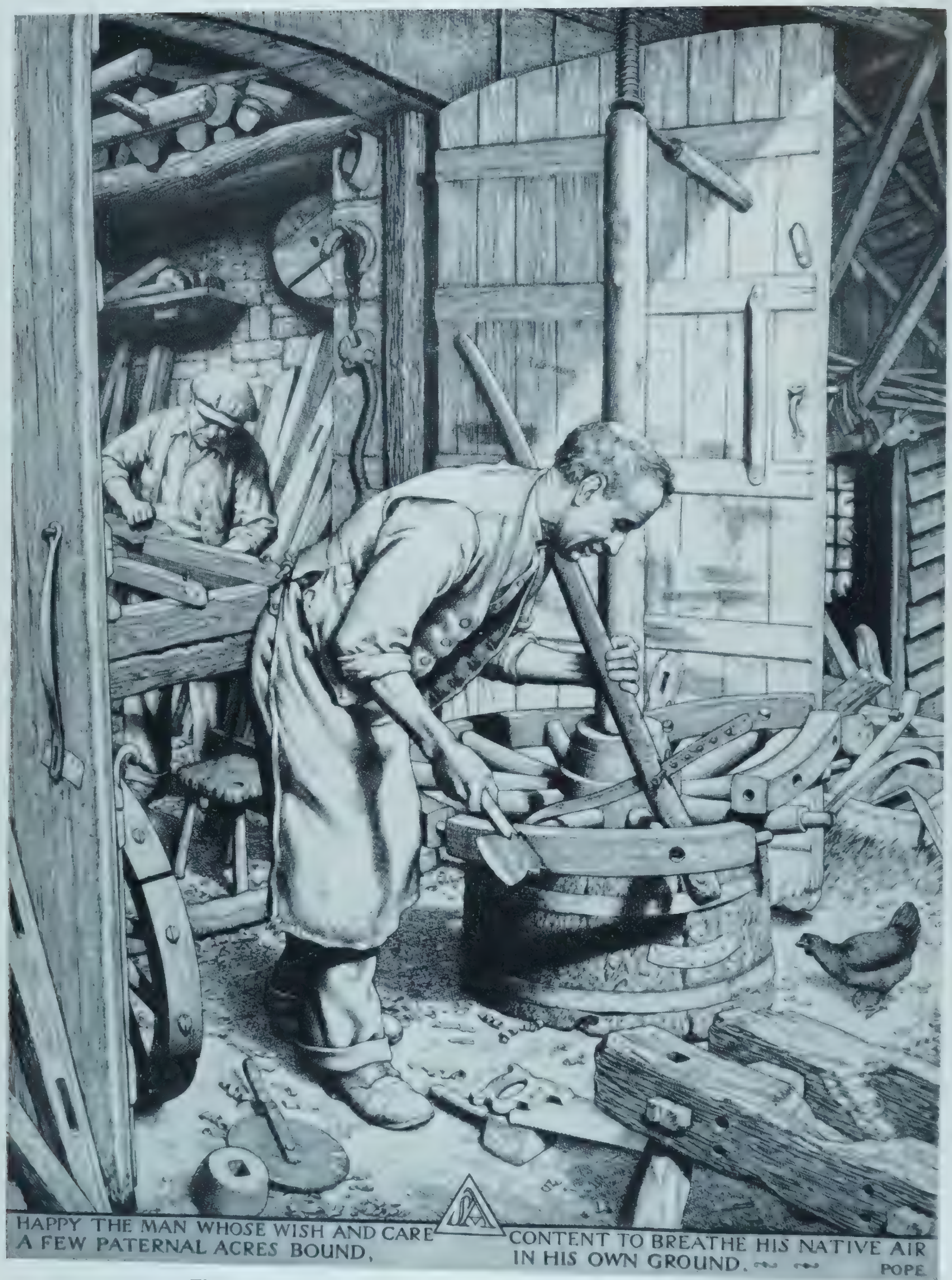


A. *Interior of the substructure of the post-mill at Parham, Suffolk, showing the post, the cross-trees on which it rests, and the quarter-bars running from half-way up the post to the ends of the cross-trees. Above are the sheers supporting the body of the mill.* (Left centre) *An engine-driven sack-hoist.* (p 91)

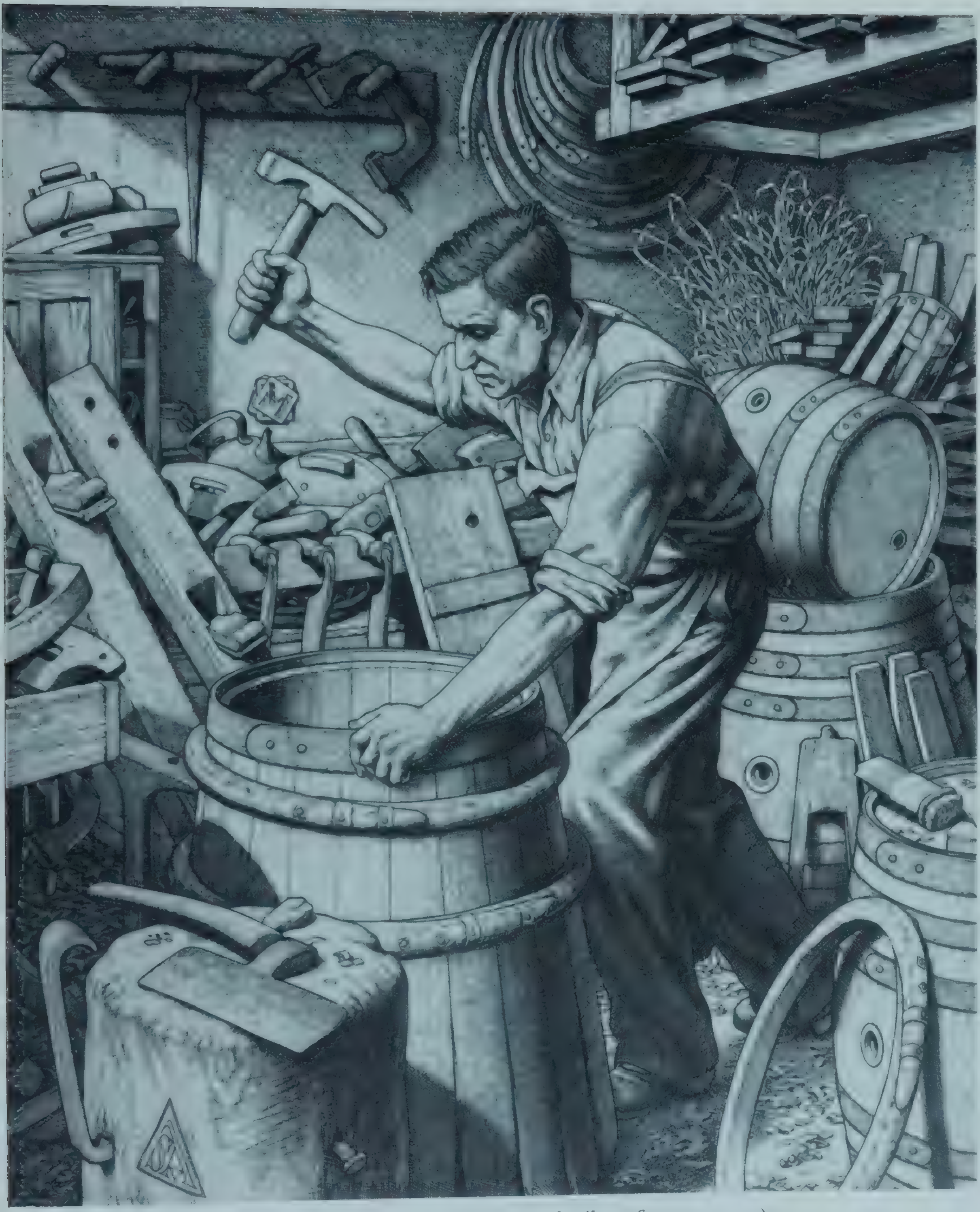


B. *The same mill, showing the drive to two pairs of stones from the brake-wheel, through the wallower (the horizontal-bevel pinion), the great spur-wheel (mounted on the same shaft), and the stone-nuts (shown disengaged).* (p 104)

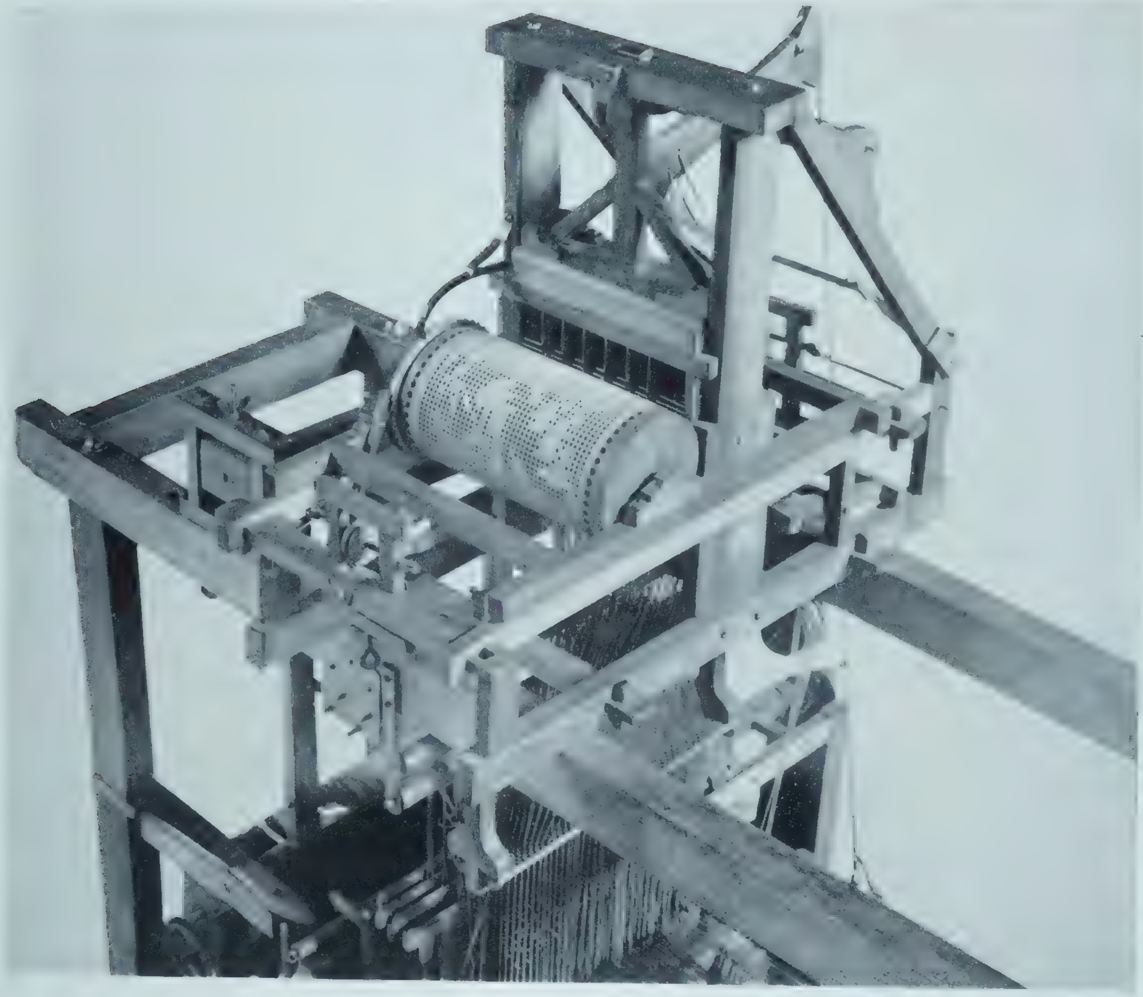
PLATE 6


HAPPY THE MAN WHOSE WISH AND CARE
A FEW PATERNAL ACRES BOUND,
CONTENT TO BREATHE HIS NATIVE AIR
IN HIS OWN GROUND.
POPE

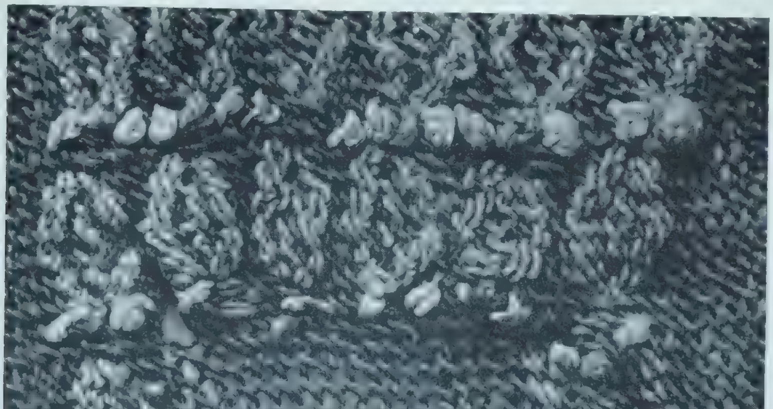
The wheelwright's workshop. (*For descriptive details see figure* 71, p 125)



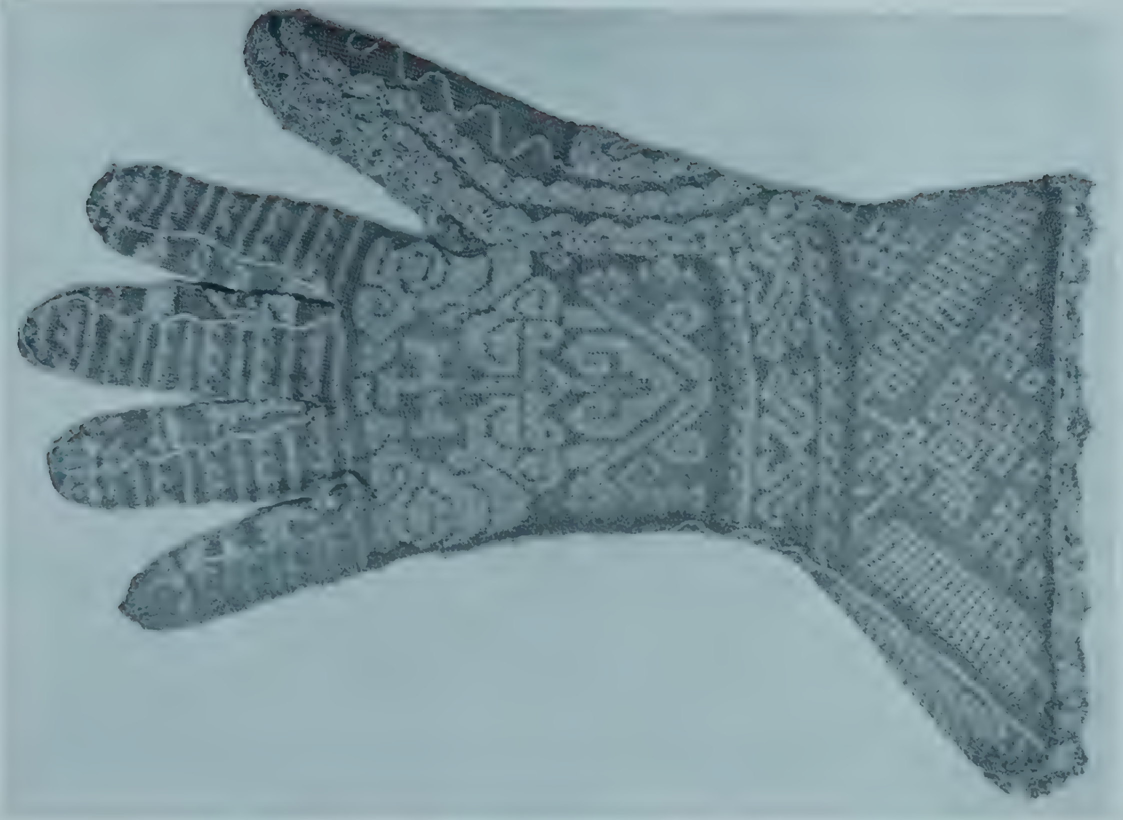
The cooper's workshop. (For descriptive details see figure 72, p 131)



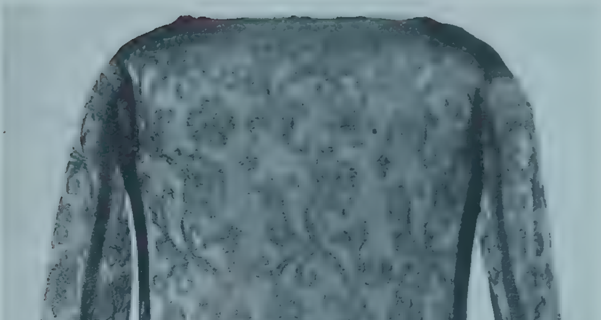
A. *Vaucanson's loom, showing the selecting device above the sheds with its perforated cylinder. 1750.* (pp 166, 169)



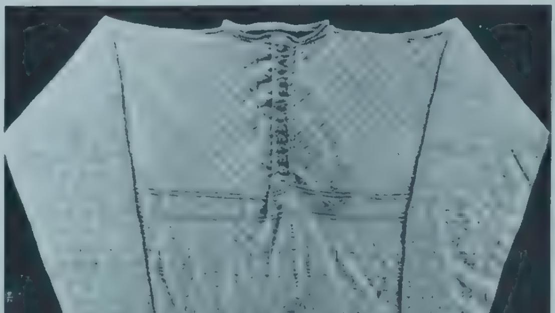
B. *Detail of* sprang *fabric.* (p 182)



A. *Spanish knitted altar-glove. Eleventh century.* (p 185)

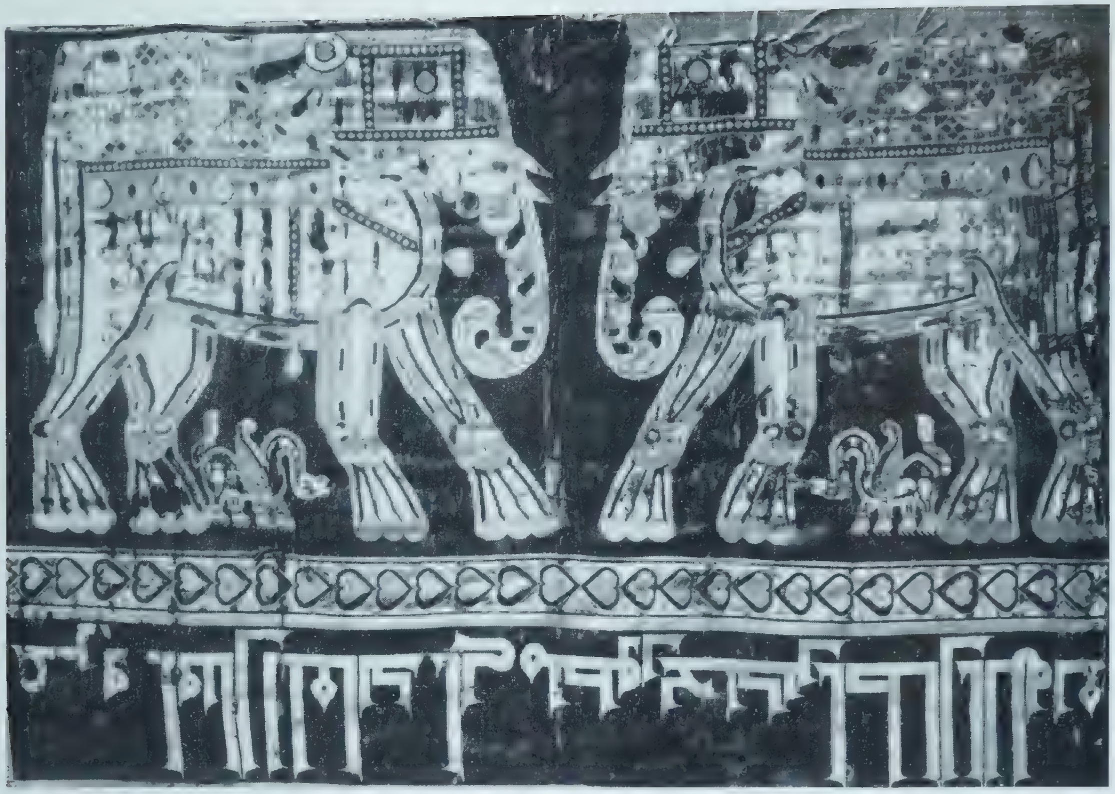


B. *Florentine coat in brocaded knitting. Sixteenth century.* (p 185)

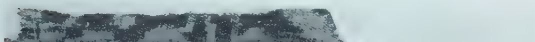


C. *Charles I's vest in patterned knitting. 1649.* (p 186)

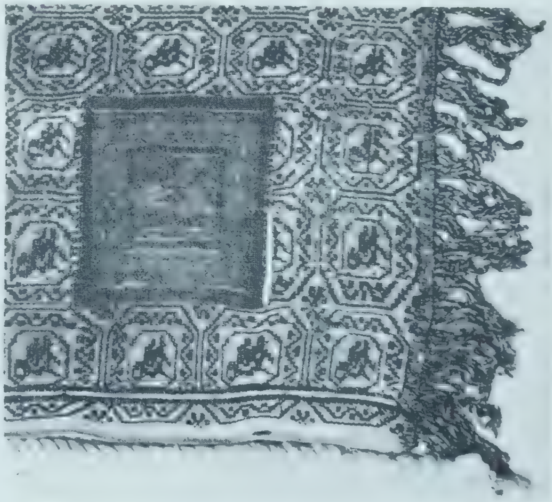
PLATE 10



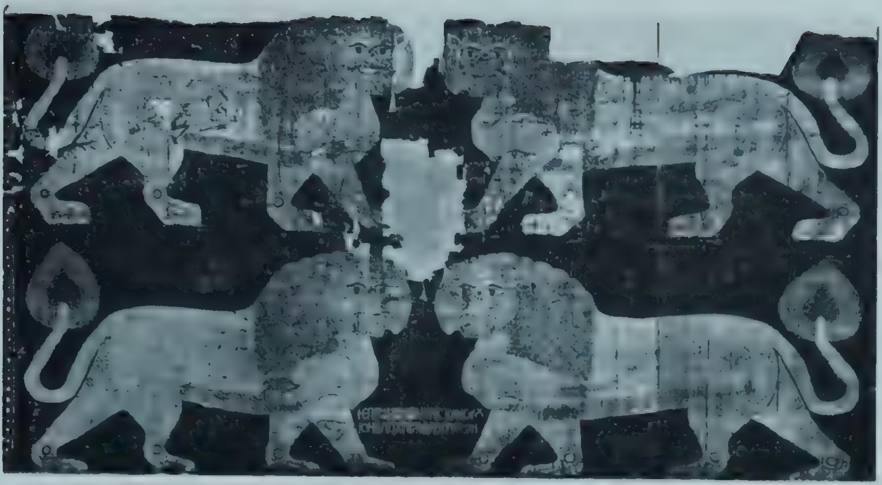
A. *Shroud of St-Josse in weft-faced figured twill weave. Islamic, tenth century. The inscription does not reverse with the rest of the design. It reads: 'The Glory and Prosperity of the Captain, Abū Manṣūr the Mighty, may God lengthen [his days]'.* (p 191)



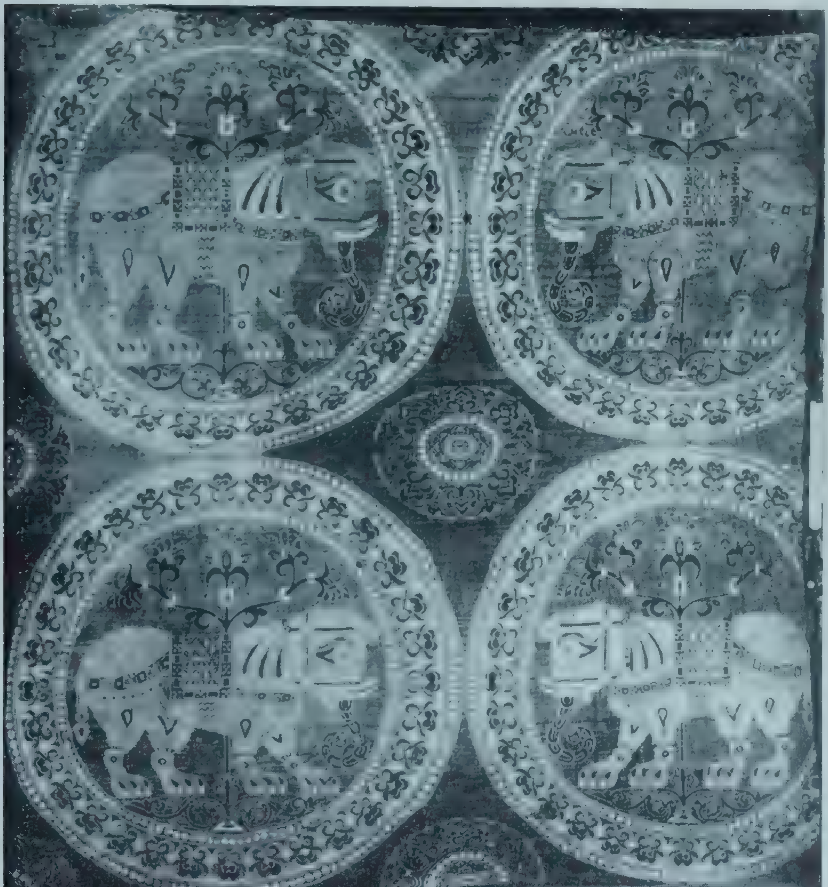
B. *Head of a gryphon, worked in weft-faced figured twill. Byzantine, tenth–eleventh centuries. Note irregular scaling and repetition of the figure picks. The roundel was at least 2 ft in diameter.* (p 192)



C. *Design in weft-faced figured tabby weave. Egypto-Roman, probably fourth century A.D. The fabric is mainly drawloom-woven with the aid of an elementary figure-harness. There are fourteen repetitions of the design in the width of the fabric and eleven in the length. The woollen fringe at the side is made from the weft-threads and the end at the bottom from the warp-ends. The tapestry panel shown in the middle of the fabric was woven with the remainder of the material and not inserted later. Its fine geometrical design is in linen weft.* (pp 193–4)

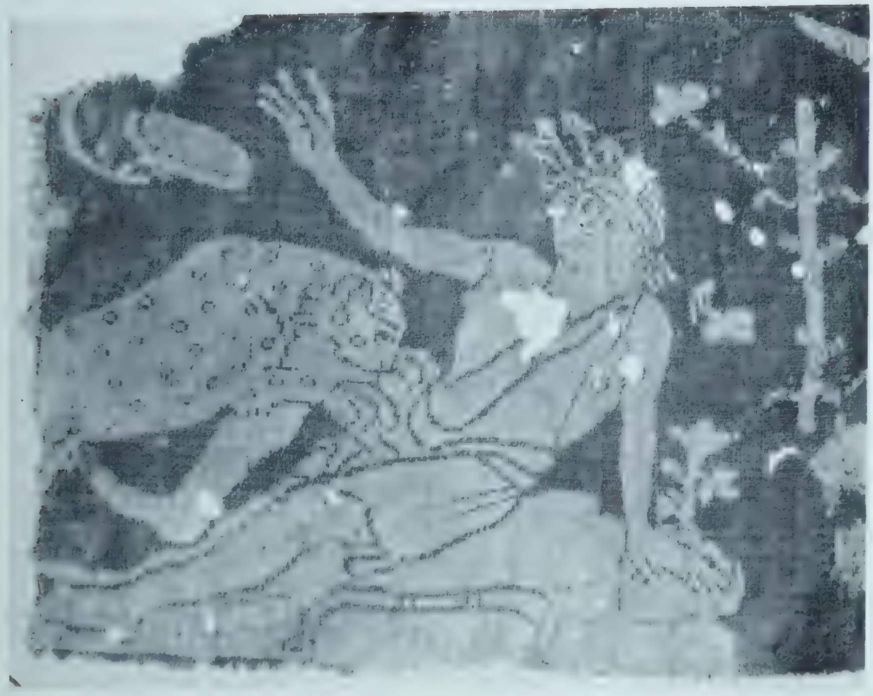


A. *Silk with lion pattern from Autinoë. Byzantine work with Persian influences. The Greek inscription, 'Under Romanos and Christophoros, Christ-loving rulers', dates the fabric to A.D. 921–32.* (pp 195, 196)

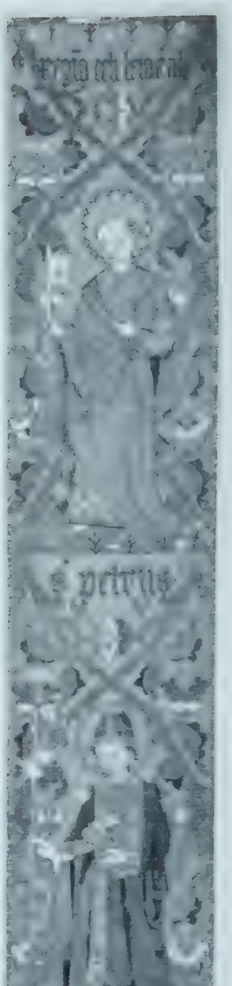


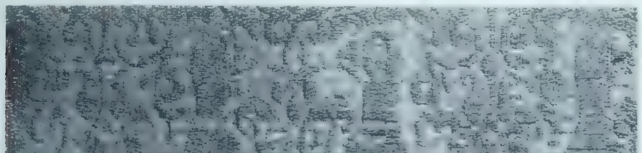
B. *'Elephant' silk from the tomb of the reburial of Charlemagne at Aachen, with the inscription of the Byzantine factory of Zeuxippos that made it. The weave is weft-faced figured twill.* c 1000. (p 196)

PLATE 12



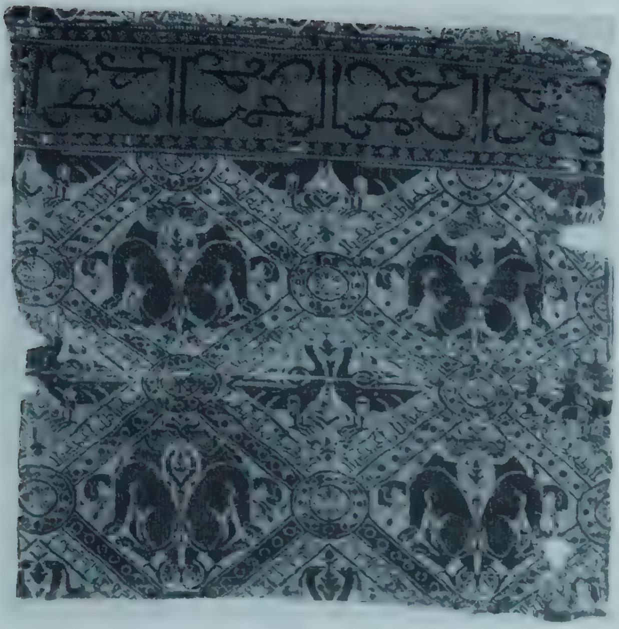
A. *The 'Maenad' silk from Sens, weft-faced figured tabby weave. Probably Hellenistic, fifth century A.D. The warp-threads are horizontal and the weft vertical. Only two wefts were used, one for the ground, the other for the design.* (p 195)



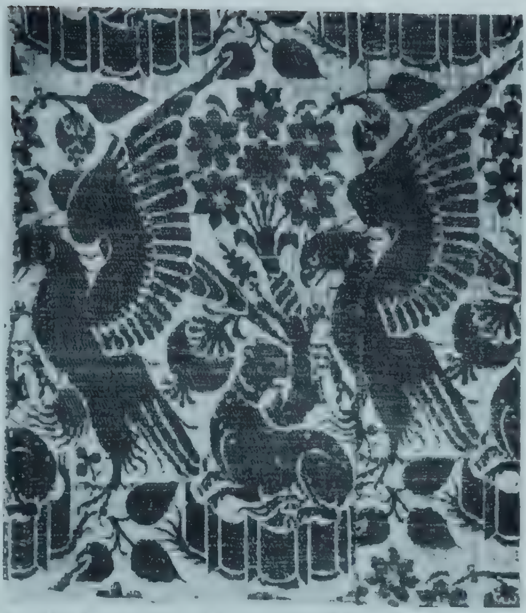


B. *Fragment of one of the robes of the Emperor Henry VI (d 1197). Sicilian, twelfth century. The weave is tabby ground tissue* (diasprum) *with a design in gold thread.* (p 198)

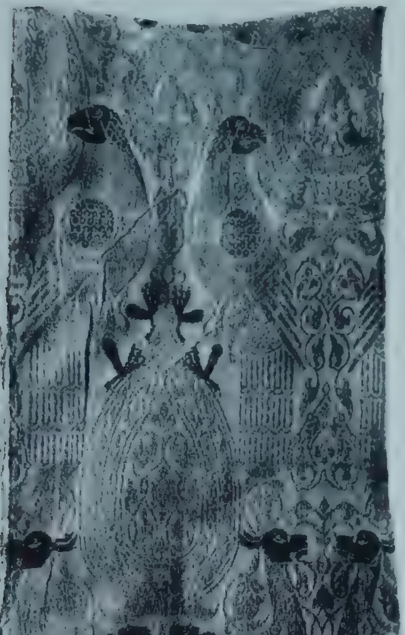
C. *German weft-faced figured twill silk. Fifteenth century. There is no repetition of the design. The main warp is of linen and the binder-warp of silk. The background is in gold thread; the faces and other details are embroidered.* (p 196)



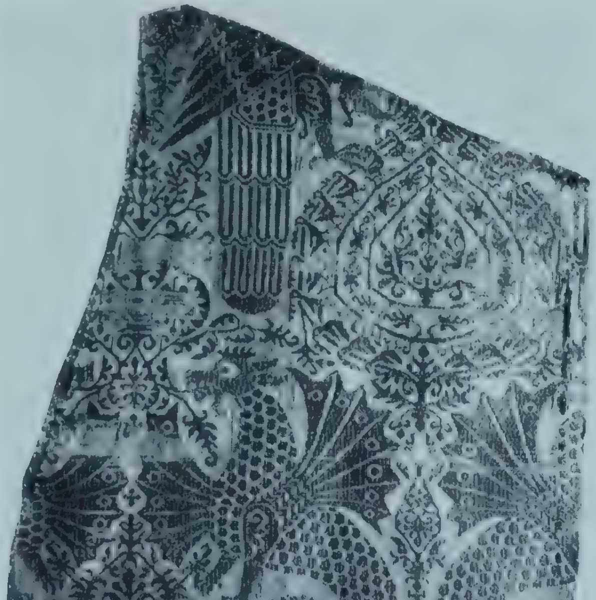
A. *Spanish tabby tissue* (diasprum). *Twelfth–thirteenth century.* (p 198)



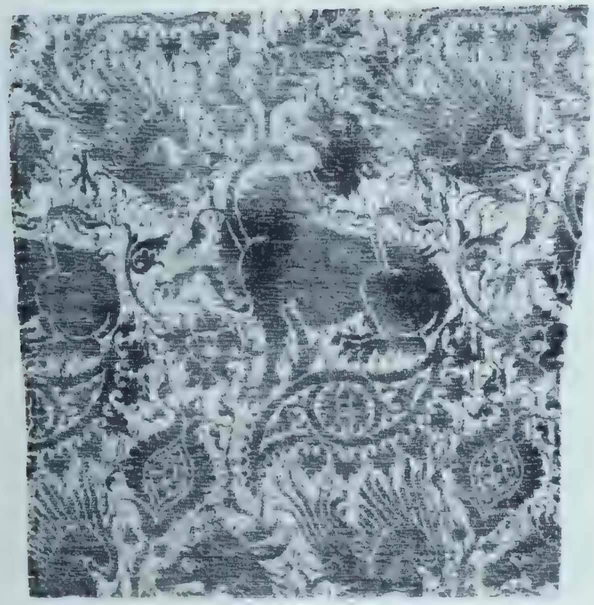
B. *North Italian silk twill-ground tissue. Fourteenth century. The design is in gold thread.* (*Warp-effect three-heald twill ground; design binding four-heald twill*). (p 199)



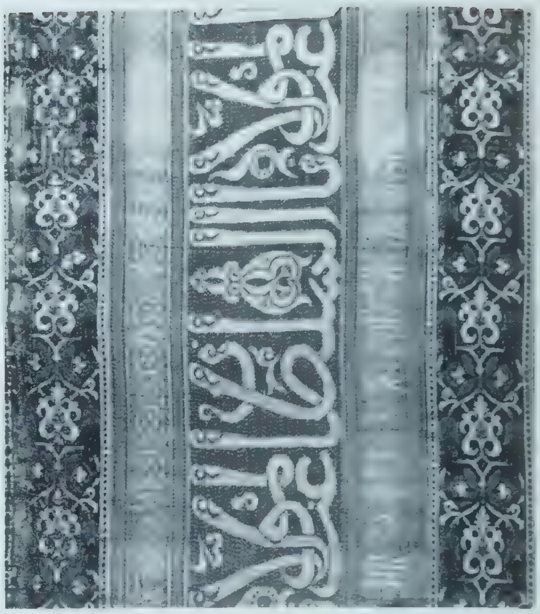
C. *Italian silk tabby thread.* (diasprum) *brocaded with metallic thread. Thirteenth century.* (p 198)



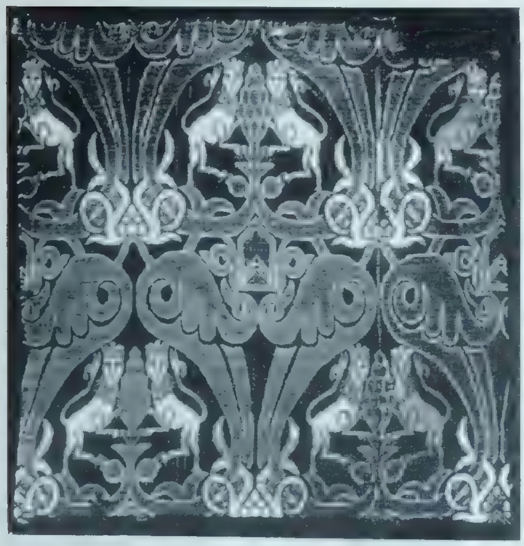
D. *Italian silk tabby tissue* (diasprum), *brocaded with gold thread and silk. Late thirteenth century.* (p 198)



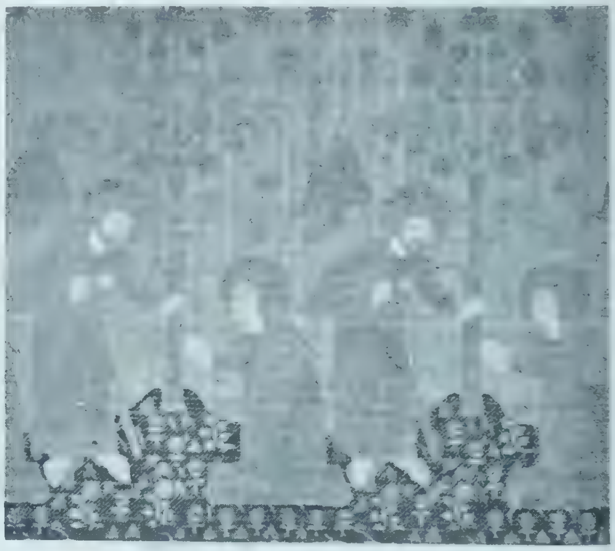
A. *North Italian silk twill-ground tissue. Fourteenth century. The design is in gold thread. (Warp-effect three-heald twill ground; design binding six-heald special twill).* (p 199)



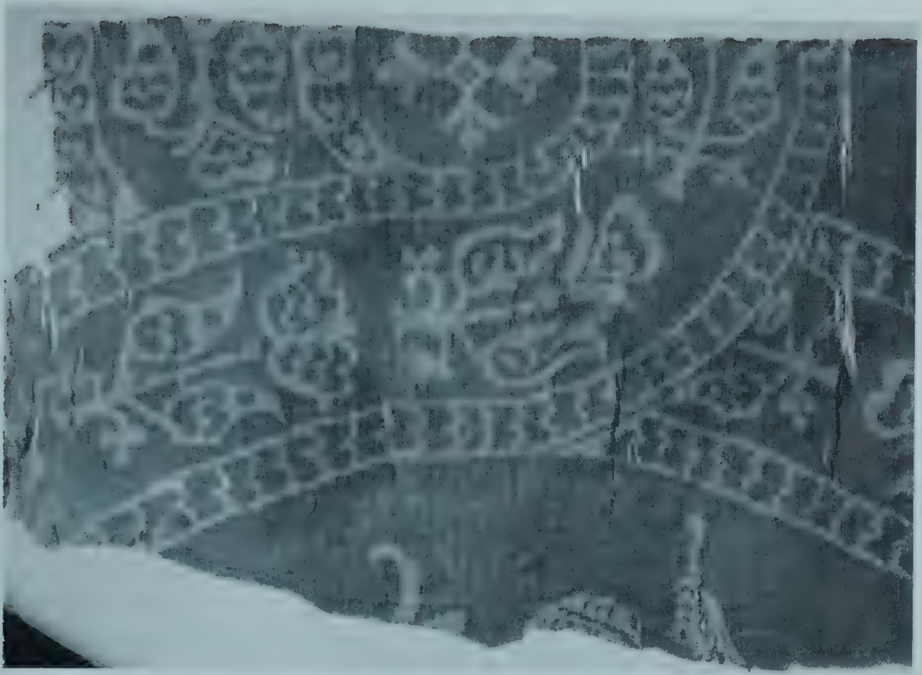
B. *Hispano-Moresque satin-ground tissue. Fourteenth century. Five-heald satin ground, and tabby binding (with binder-warp) for the design.* (p 200)



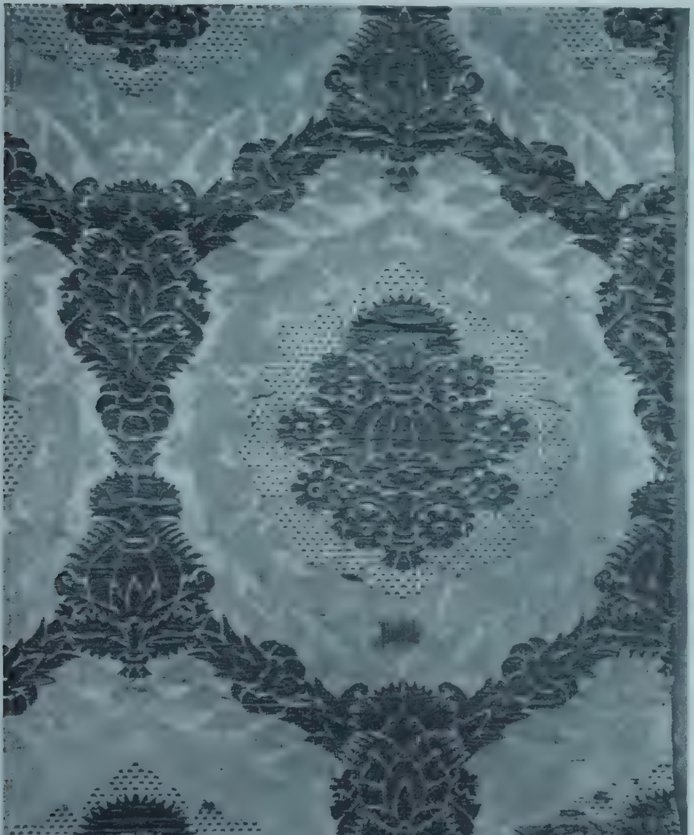
C. *Hispano-Moresque silk satin-ground tissue. Fifteenth century. Five-heald satin ground and tabby binding (with binder-warp) for the design.* (p 200)



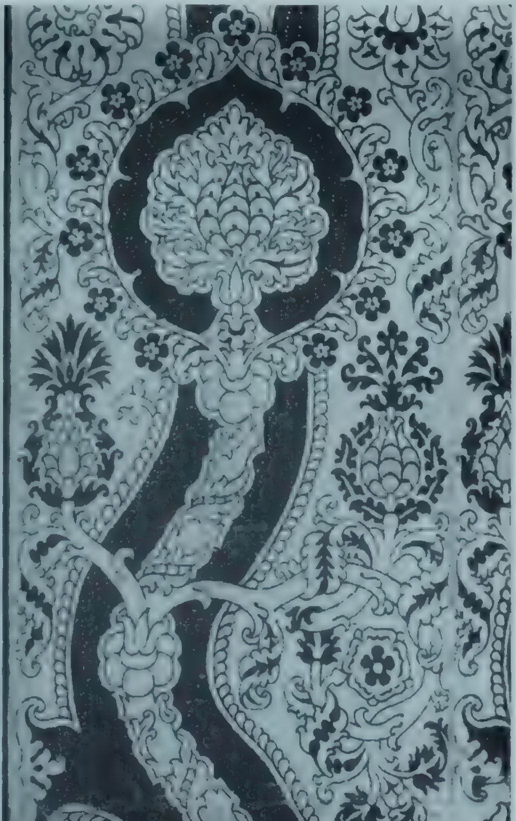
D. *Italian silk brocatelle. Fifteenth century. Christ, Mary Magdalene, and the tree are in gold thread; the faces, hands, and feet in white silk. Five-heald satin ground.* (p 200)



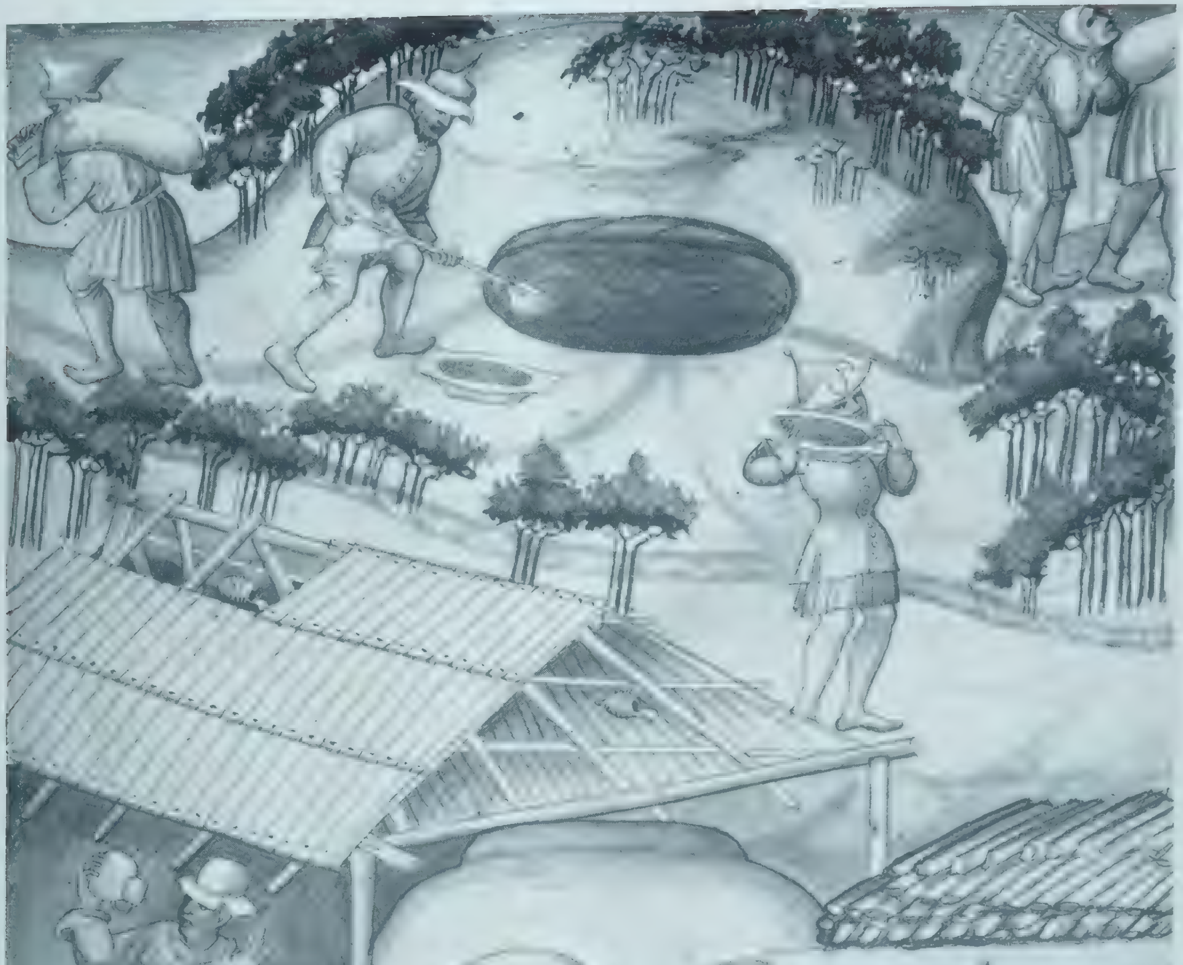
A. *Four-heald twill damask silk, from the Treasury of St Servatius, Maastricht. Early Byzantine (?).* (p 202)



B. *Italian brocaded damask. Fifteenth century. Warp-effect five-heald satin ground, with design in weft-effect five-heald satin, brocaded in metal thread with special binding.* (p 203)

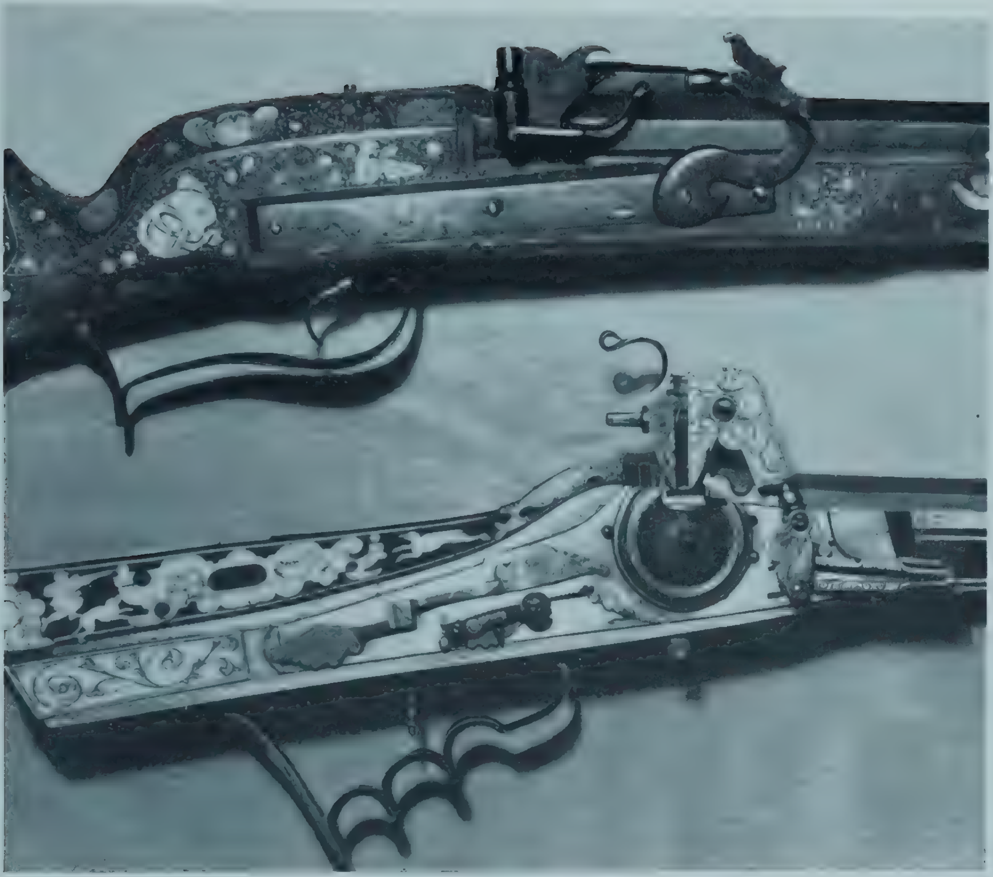


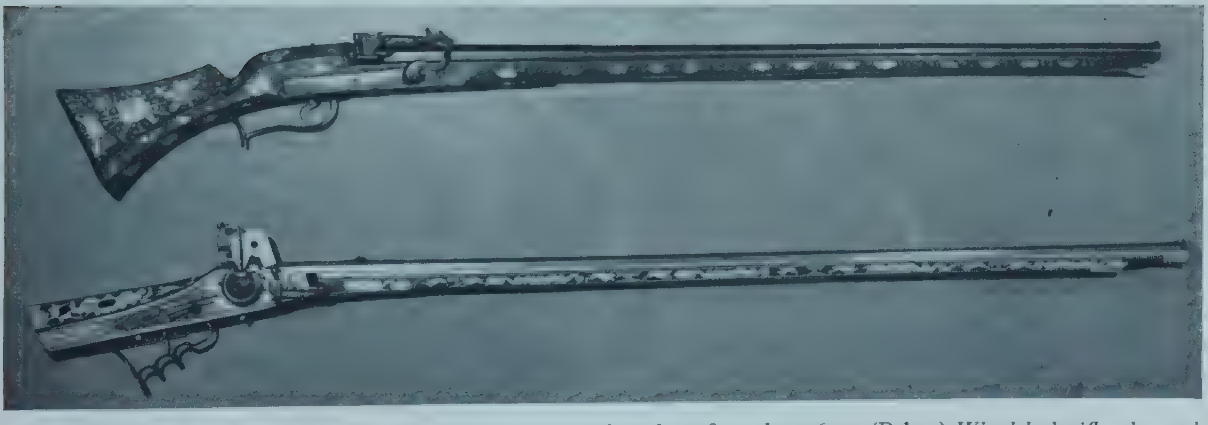
C. *Italian figured velvet with gold* bouclé *weft enrichment. Fifteenth century.* (p 205)



Manuscript miniature showing a glass-house at work. Bohemia, c *1420* (cf vol II, figure 310). (pp 207, 208)

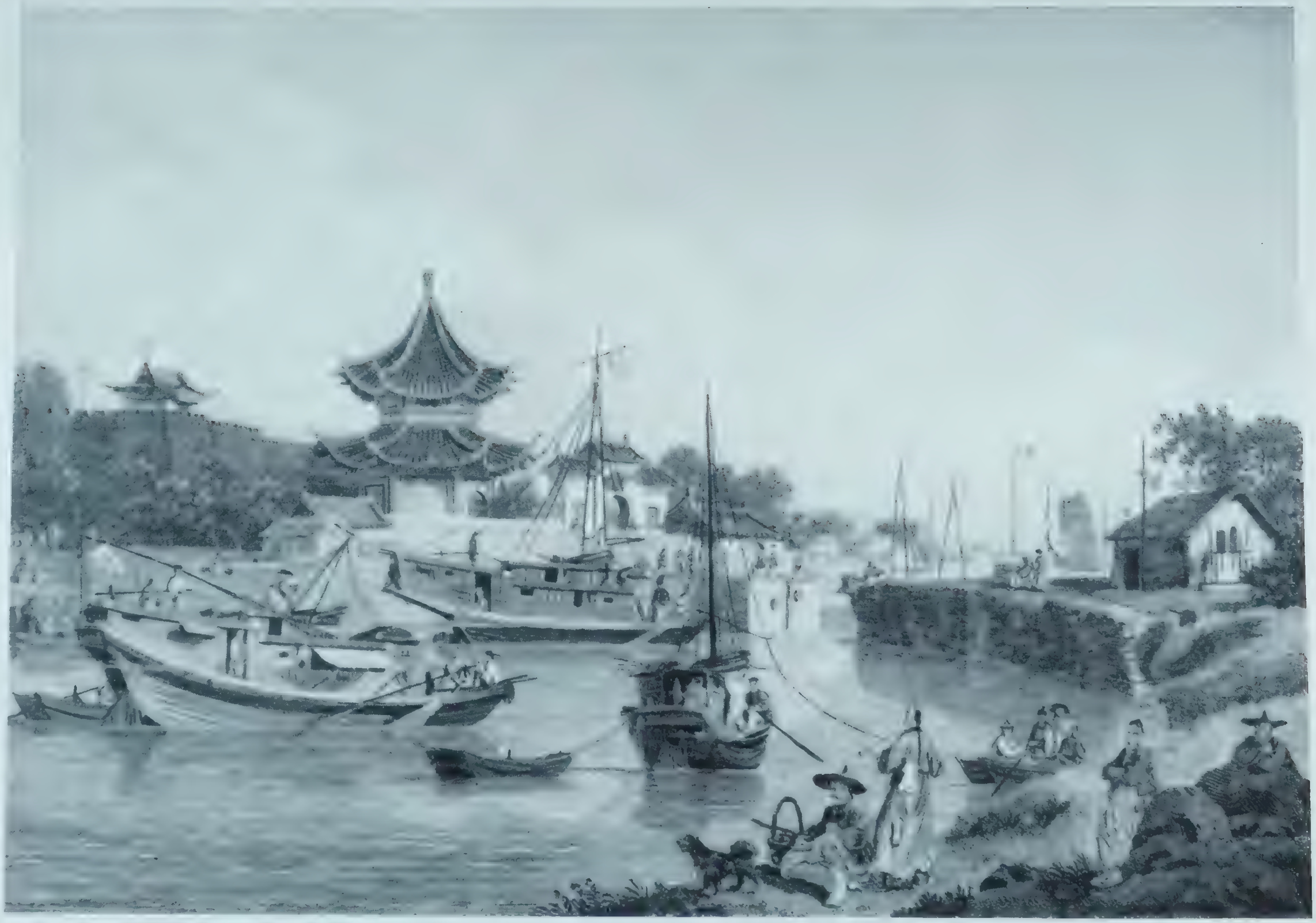
PLATE 17





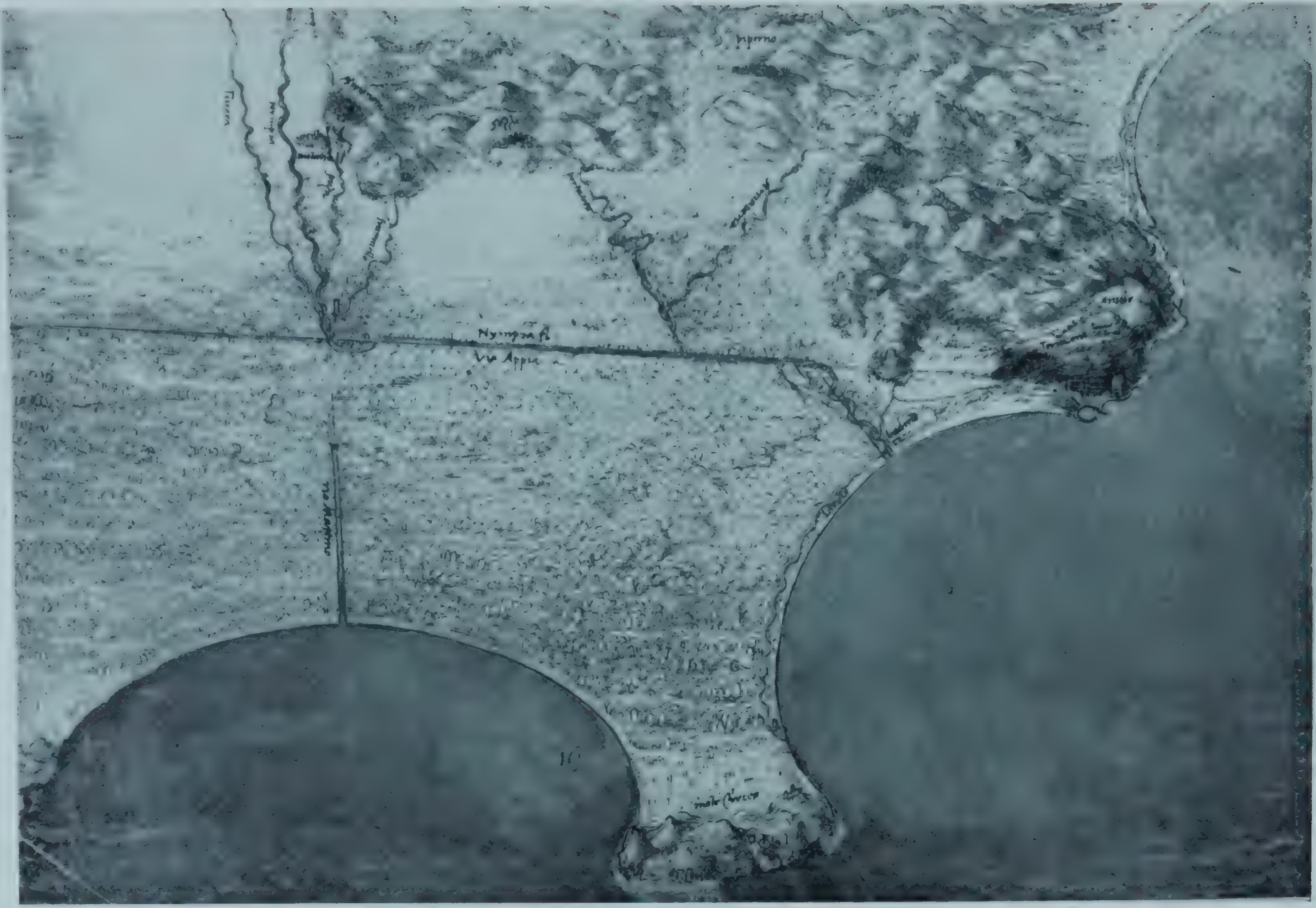
(Above) *Matchlock gun, the stock inlaid with brass wire and mother-of-pearl,* c *1600.* (Below) *Wheel-lock rifle, the stock inlaid with ivory. German, 1593. The details show the locks.* (pp 355, 356, 358)

PLATE 18

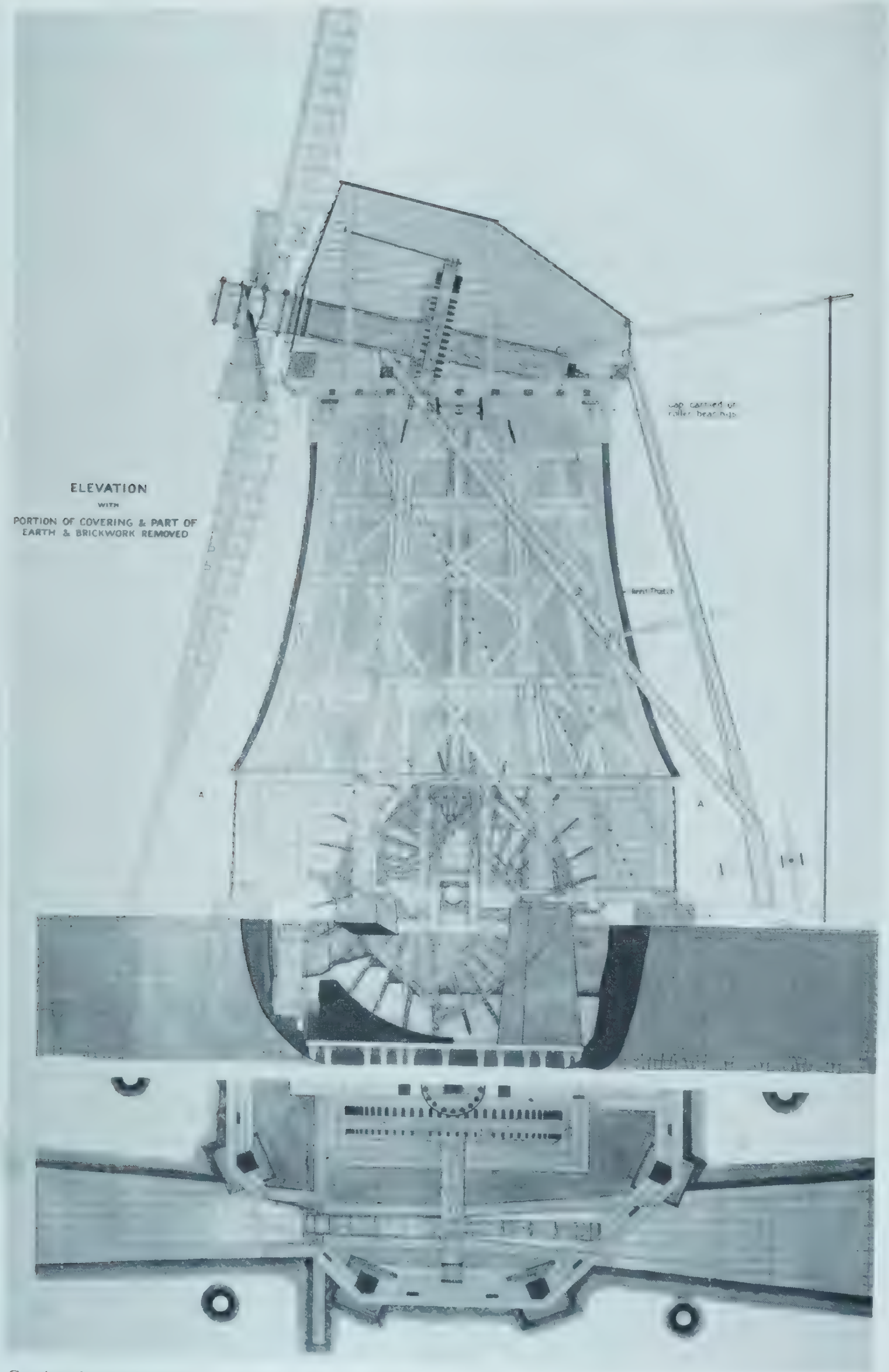


Chinese barge passing through a stop-log gate on the Grand Canal. From Staunton, 1797. (p 439)

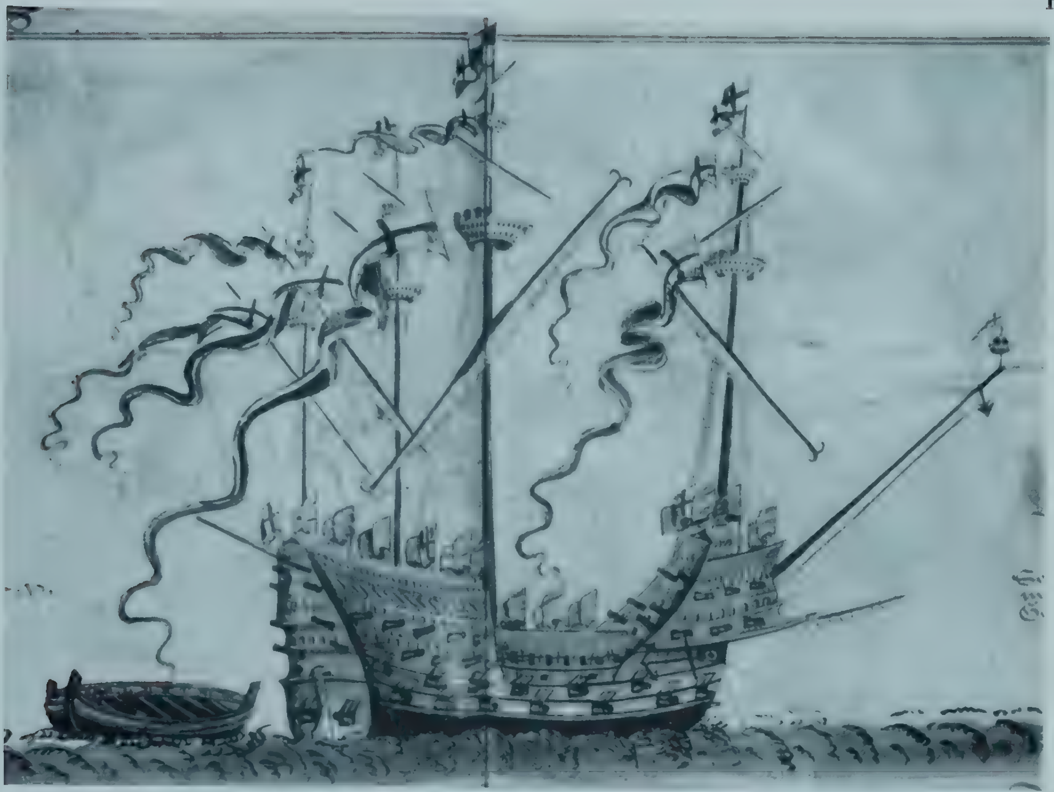
PLATE 19



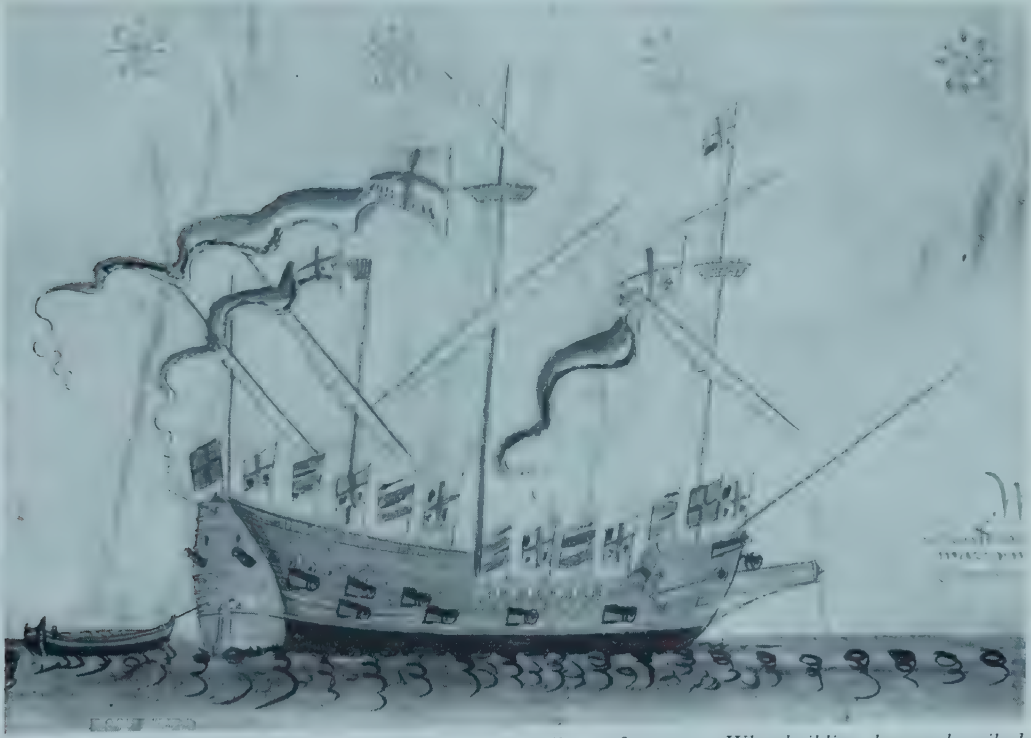
Leonardo da Vinci's plan for draining the Pontine Marshes. 1515. (p 311) cf figure 207


ELEVATION
WITH
PORTION OF COVERING & PART OF EARTH & BRICKWORK REMOVED
Cap carried on roller bearings
Reed Thatch
A
A

Sectional diagram (reconstructed) of a Dutch wind-driven scoop-wheel of the early eighteenth century. (Above) *Elevation;* (below) *plan across the line* AA. *The cap bearing the sails is supported on roller bearings; the main part of the structure is covered with reed thatch. The scoop-wheel rotates clockwise. Scale 1/134.* (pp 106, 321)

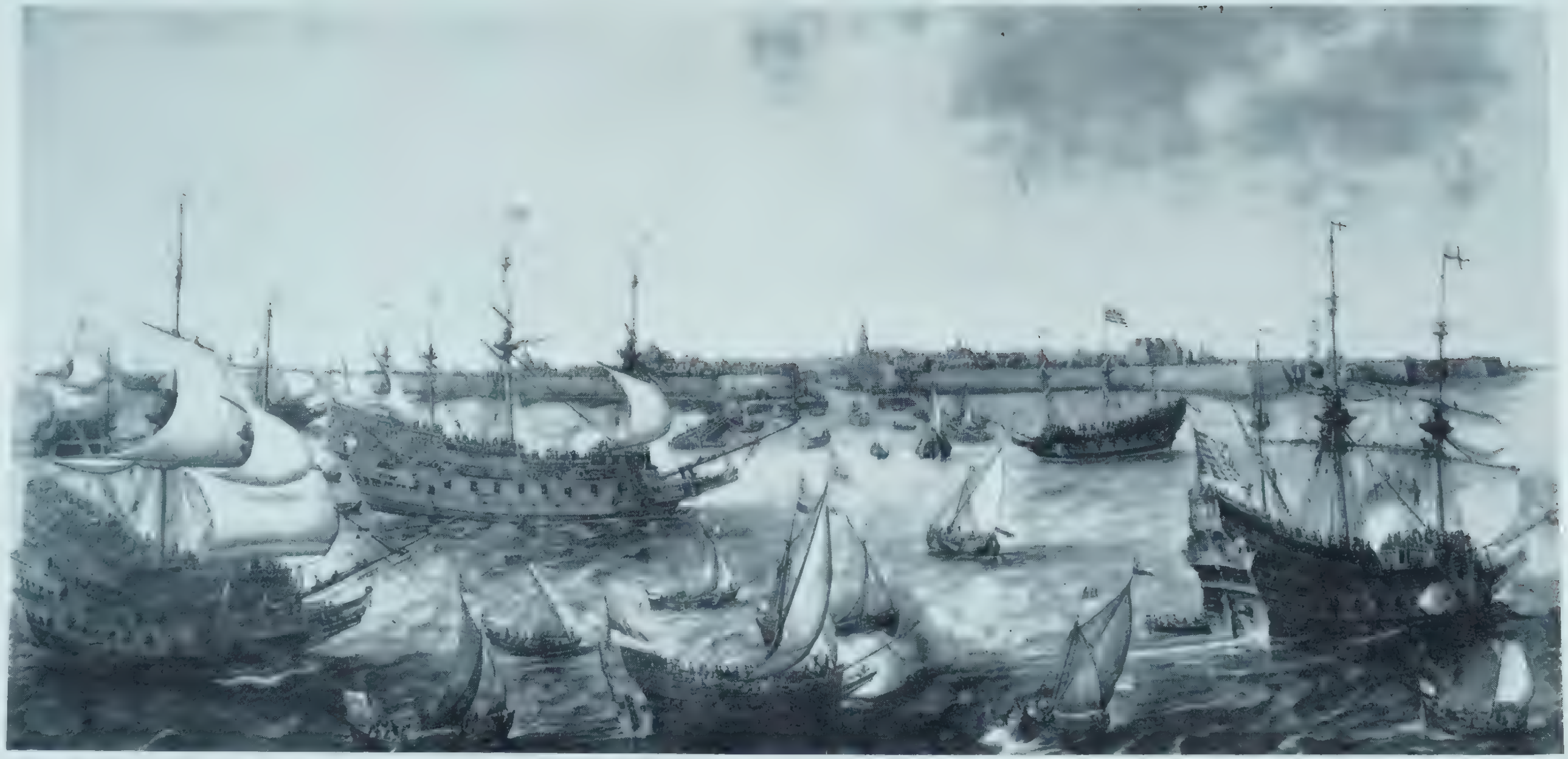


A. *The* Henry Grâce à Dieu, *Henry VIII's biggest warship, when rebuilt in 1545, was of 1000 tons. She carried 21 heavy brass guns, 130 iron guns, and 100 hand-guns. Her crew of 700 consisted of 349 soldiers, 301 marines, and 50 gunners. Each of her four masts was in three pieces with two topcastles. Many of her guns fired through gun-ports and her fore- and after-castles were designed to be defended against an enemy boarding the low waist or middle of the ship.* (pp 478, 487)

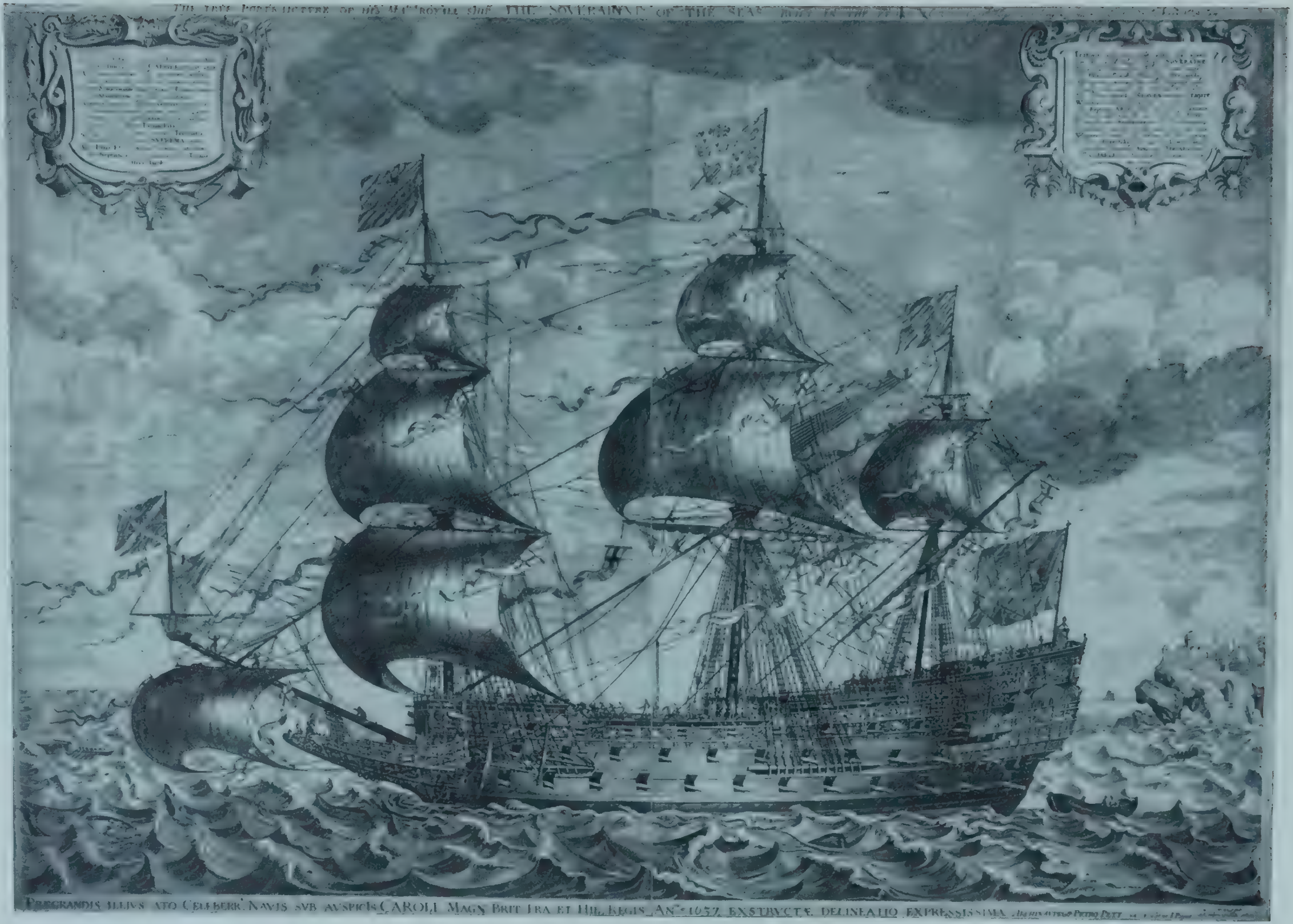


B. *The* Grand Mistress, *built in 1545 and classed as a galleass of 450 tons. When building she was described as a 'great galleon'. She has a beak-head similar to a galley's, and a heavy gun in the bow. The fore- and after-castles are much lower than was usual in the older ships.* (p 479)

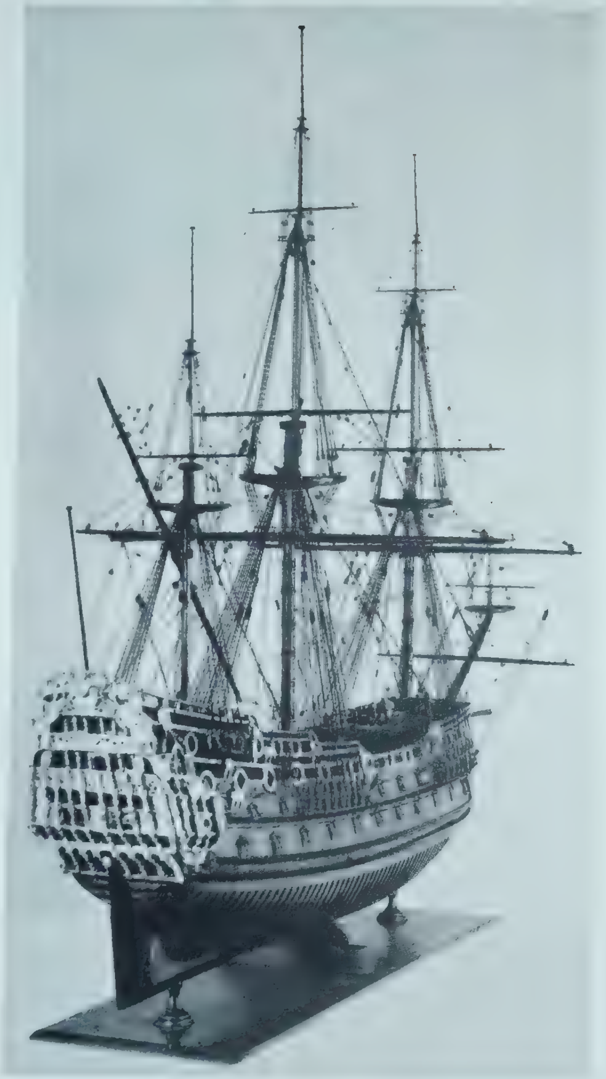
PLATE 22



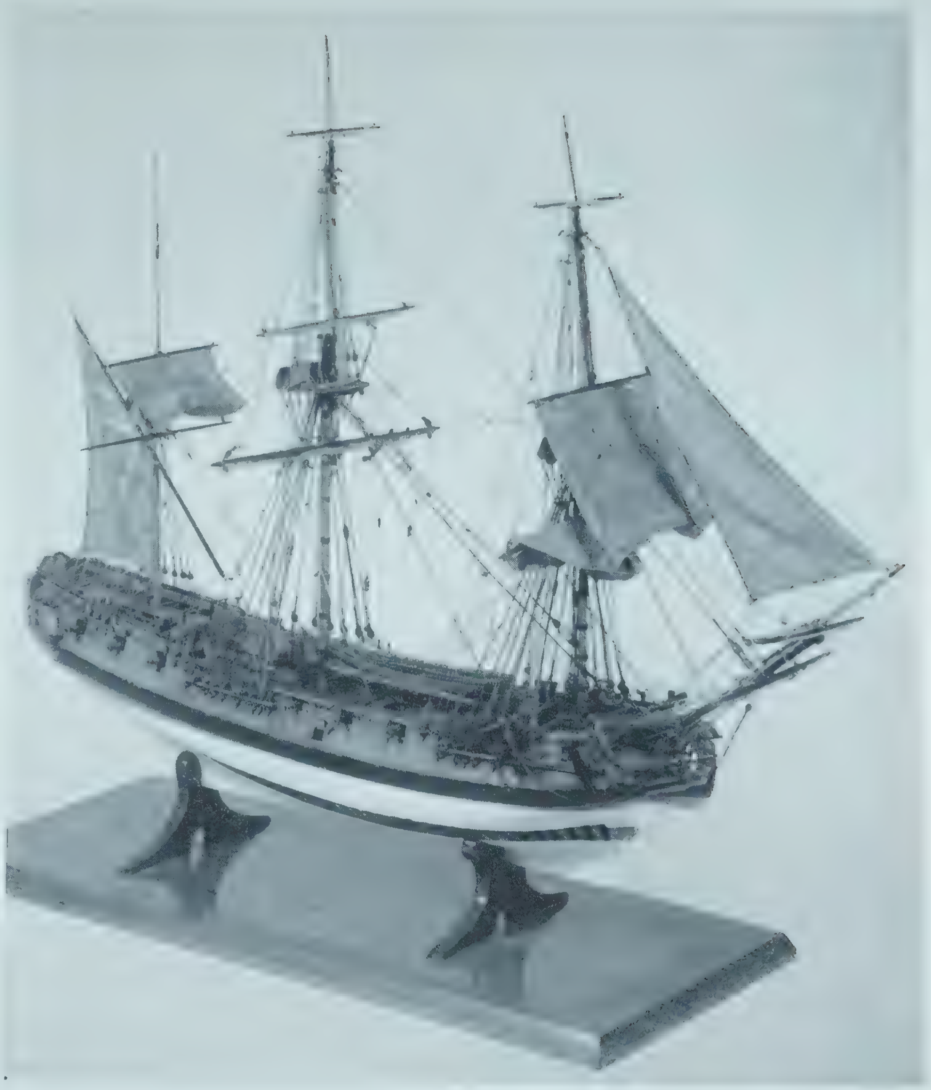
The arrival of the Elector Palatine with his bride at Flushing, 1613. The principal ship is the Royal Prince *of 1200 tons, 55 guns, built in 1610 by Phineas Pett. She was 210 ft long over-all, 115 ft long on the keel, and of* $43\frac{1}{2}$*-ft beam. The vessel was a four-master in the tradition of the preceding century, but carried square mizzen-topsails and also the spritsail topmast and sail at the end of the bowsprit. From a painting of 1623 by Hendrik Cornelisz Vroom (1566–1640).* (pp 482, 485, 486, 494)


THE TRVE PORTRAICTVRE OF HIS MA.TIES ROYALL SHIP THE SOVERAIGNE OF THE SEAS
PERGRANDIS ILLIVS ATQ CELEBERR. NAVIS SVB AVSPICIS CAROLI MAGN BRIT FRA ET HIB REGIS AN° 1637 EXSTRVCTÆ DELINEATIO EXPRESSISSIMA

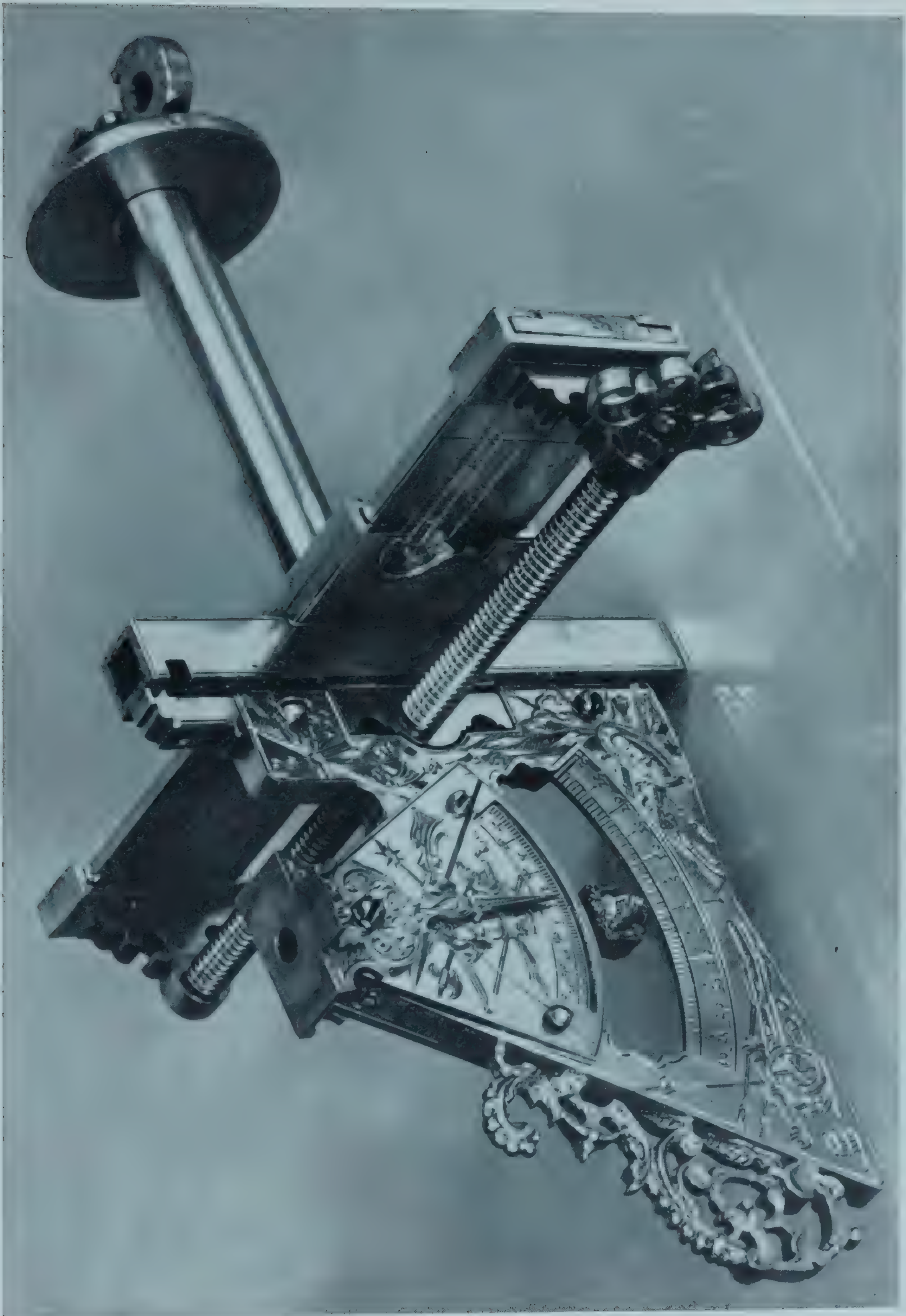
The Sovereign of the Seas, *built at Woolwich by Phineas Pett in 1637, of 1522 tons and 100 guns, was larger than the* Royal Prince, *being 232 ft long overall, 128 ft on the keel, and of 48-ft beam. Her guns were mounted on three complete gun decks, so that she was a three-decker like Nelson's* Victory. *She had three masts only and a very lofty sail-plan with royal sails on the fore- and main-masts.* (pp 482, 485–6, 494)



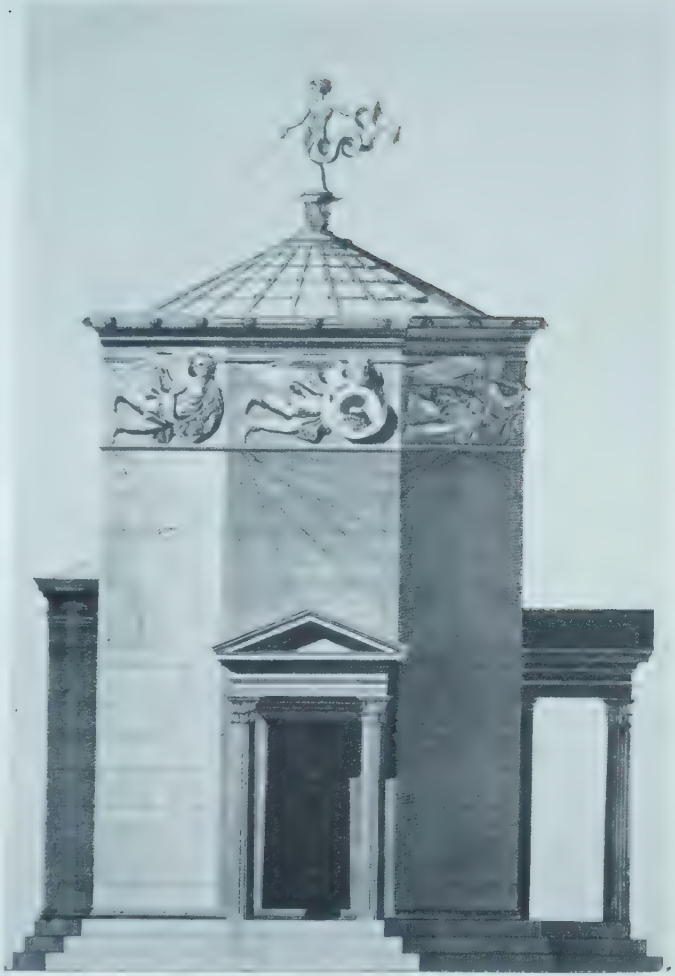
A. *Contemporary scale model of a proposed 90-gun ship, c 1675, showing the elaborate carving decorating the stern and quarter galleries. She was three-decked and would have served as a flagship. The scale of the model, $\frac{1}{4}$-in to 1 ft, was usual in English models at this time. The rigging has been renewed but the spars are original.* (pp 482, 490)



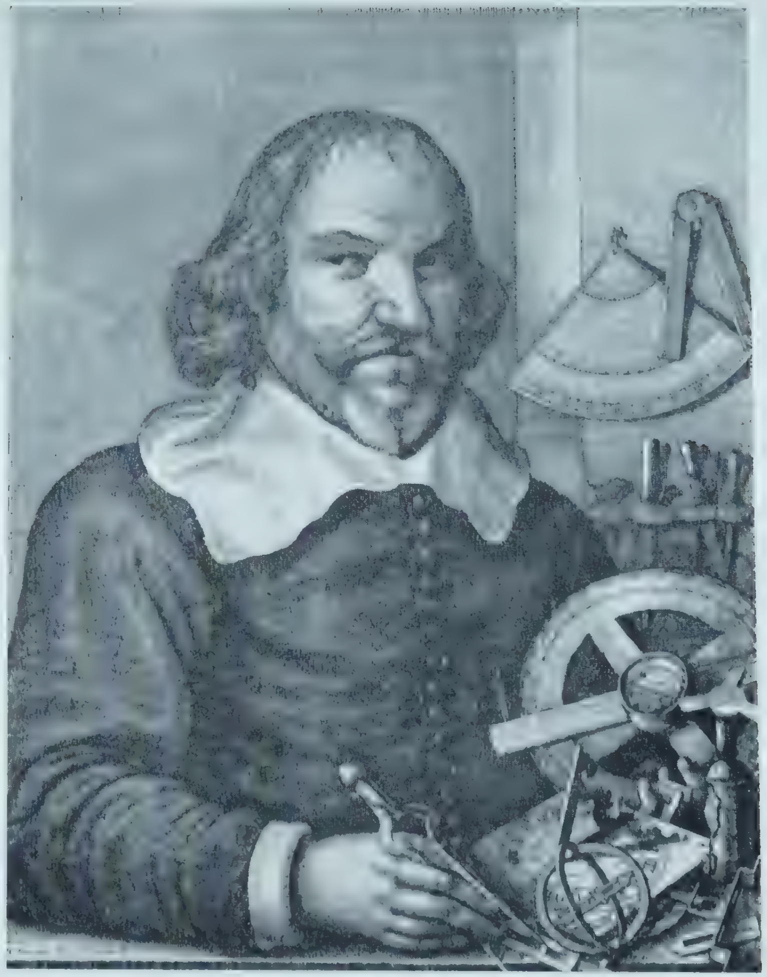
B. *Contemporary rigged scale model of the* Tartar, *20 guns, 1734. The sails and rigging are original. The mizzen and jib are set, the fore and mizzen topsails are loosed. The long-boat can be seen stowed on the booms, the spare spars carried on deck amidships.* (pp 482, 490)



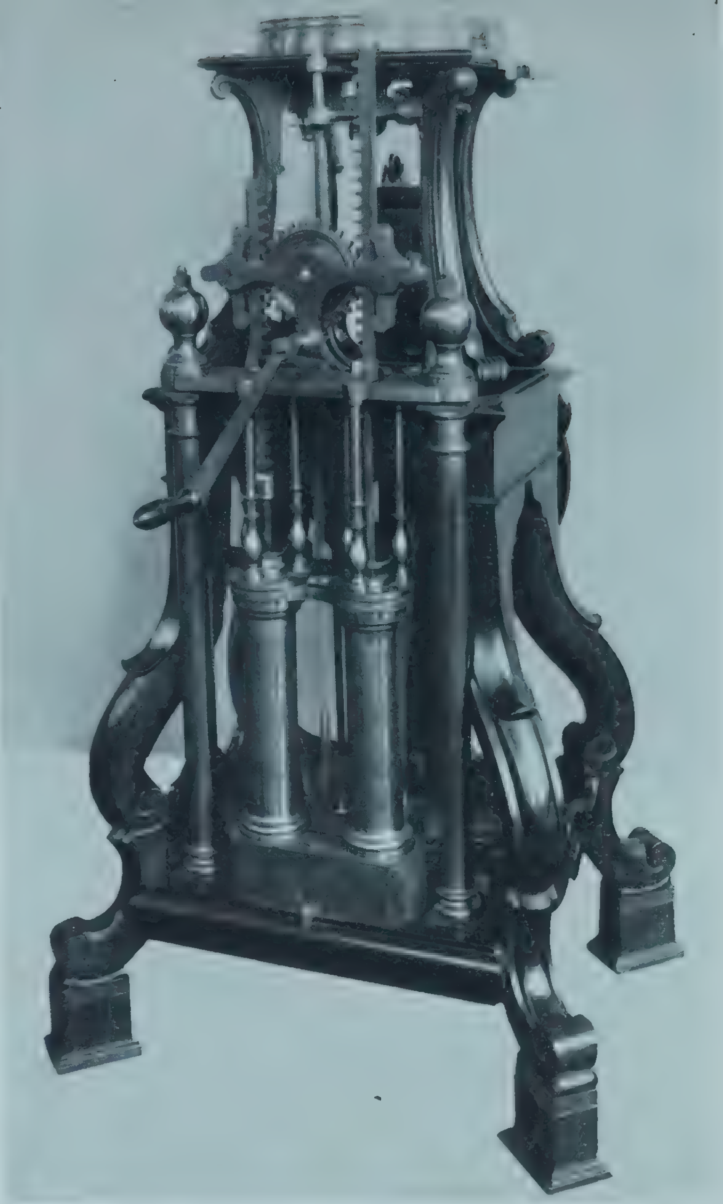
Gunner's level by Christopher Trechsler, 1614. Note the delicate decoration and the beautifully cut traversing-screw. (pp 337, 375, 629)



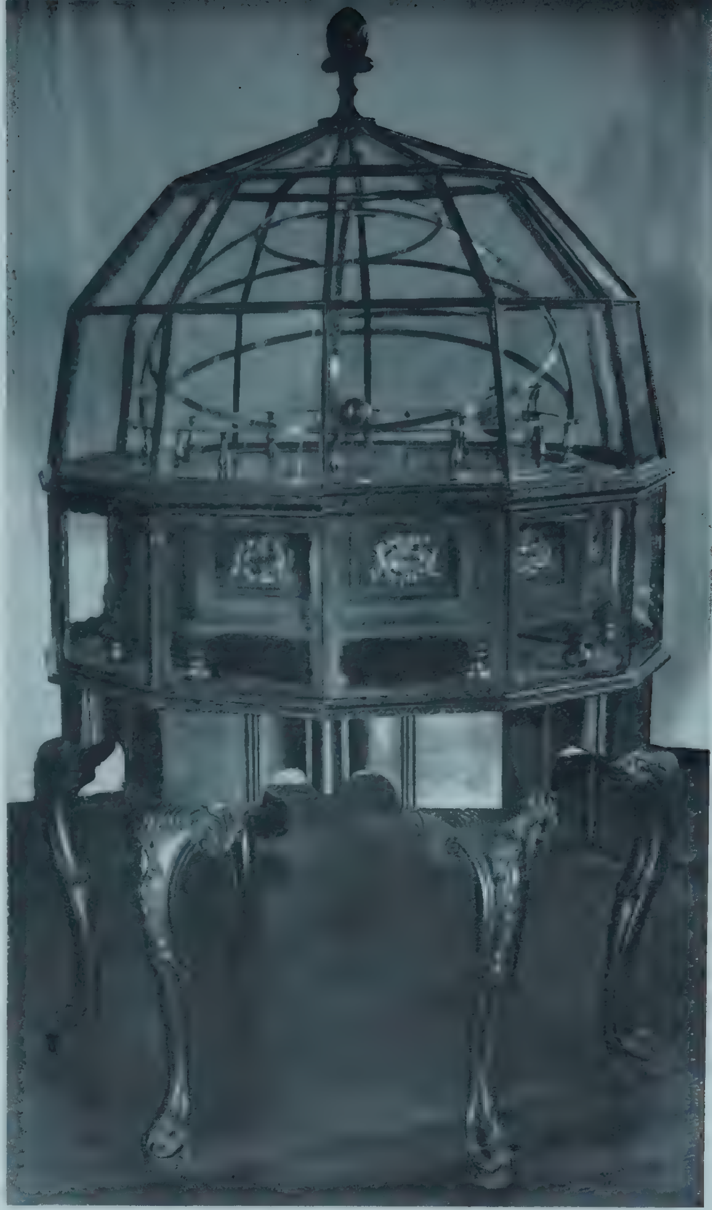
A. *The octagonal 'Tower of the Winds' at Athens. After a drawing of 1762.* (p 517)



B. *Elias Allen* (*fl* 1606–54), *with a variety of instruments:* on the table *a universal ring-dial, a horizontal dial, and a circumferentor;* on the wall *a quadrant and a sector.* (pp 630–1)

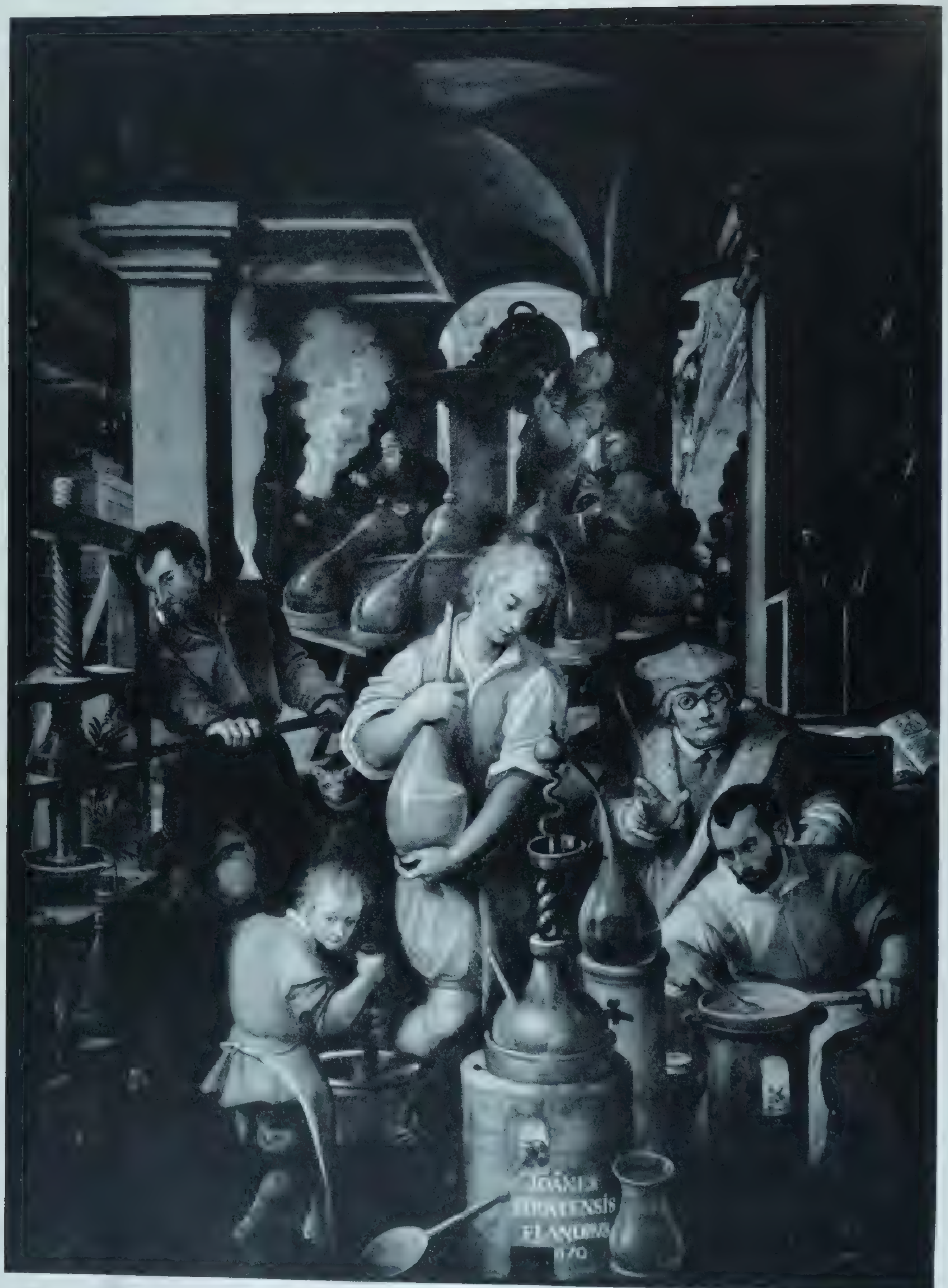


A. *George Adams's compressing and exhausting air-pump, 1762. The brass plate to which the receiver was luted is at the top of the instrument; between the pump-barrels is the manometer for measuring the pressure within it.*
(pp 637, 645)

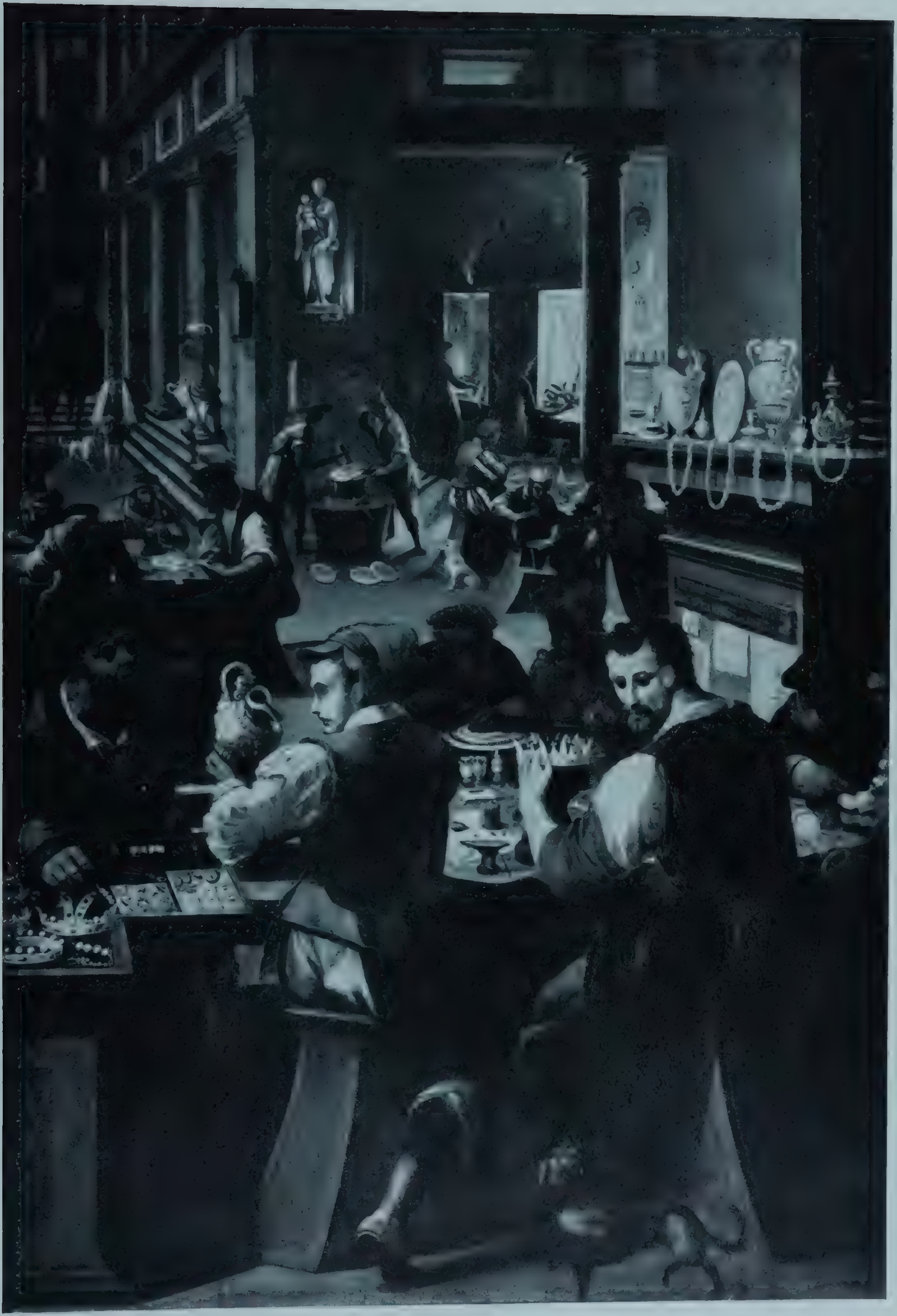


B. *Orrery (model of the solar system) by Benjamin Cole,* c *1750.*
(p 638)

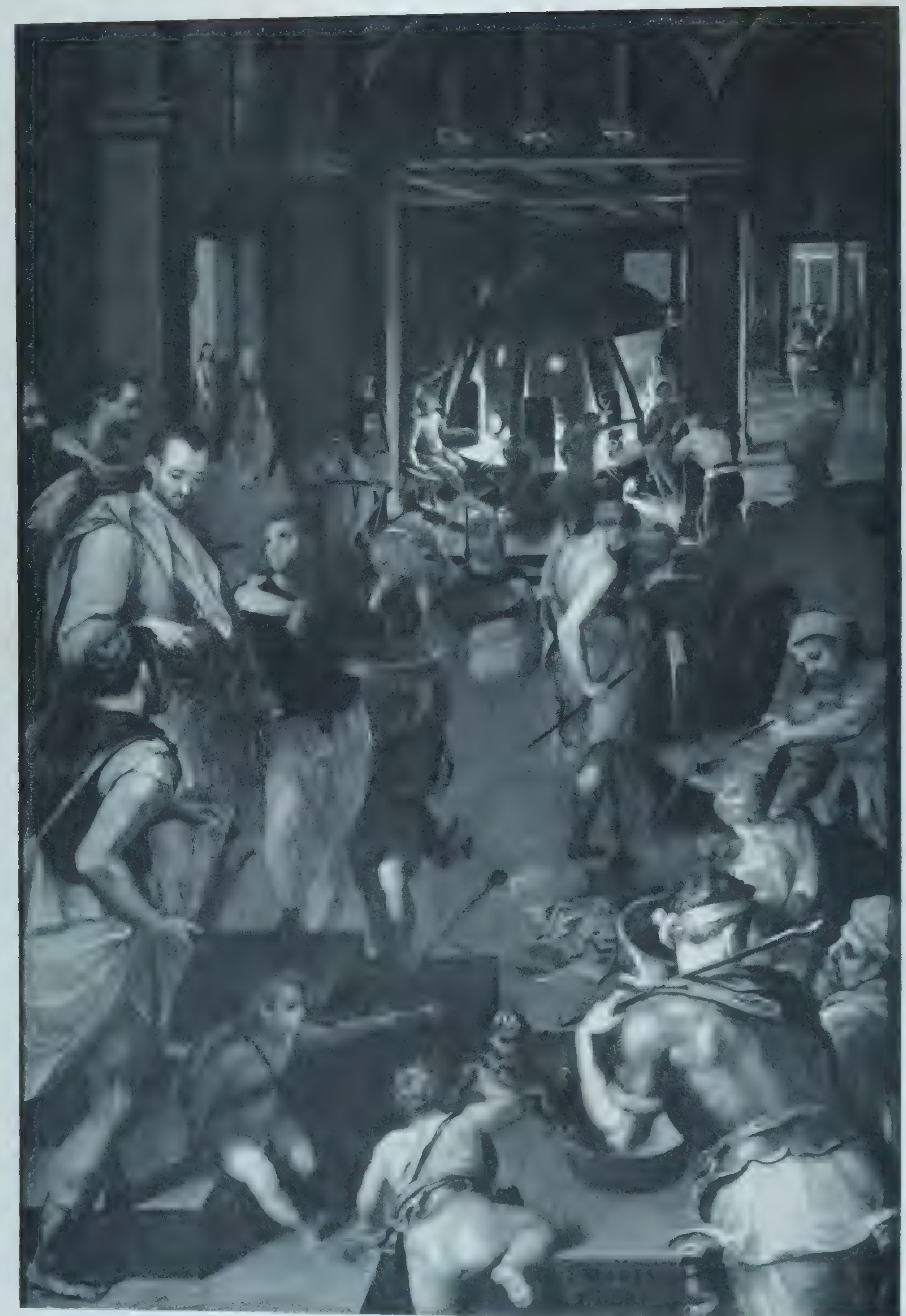
PLATE 28



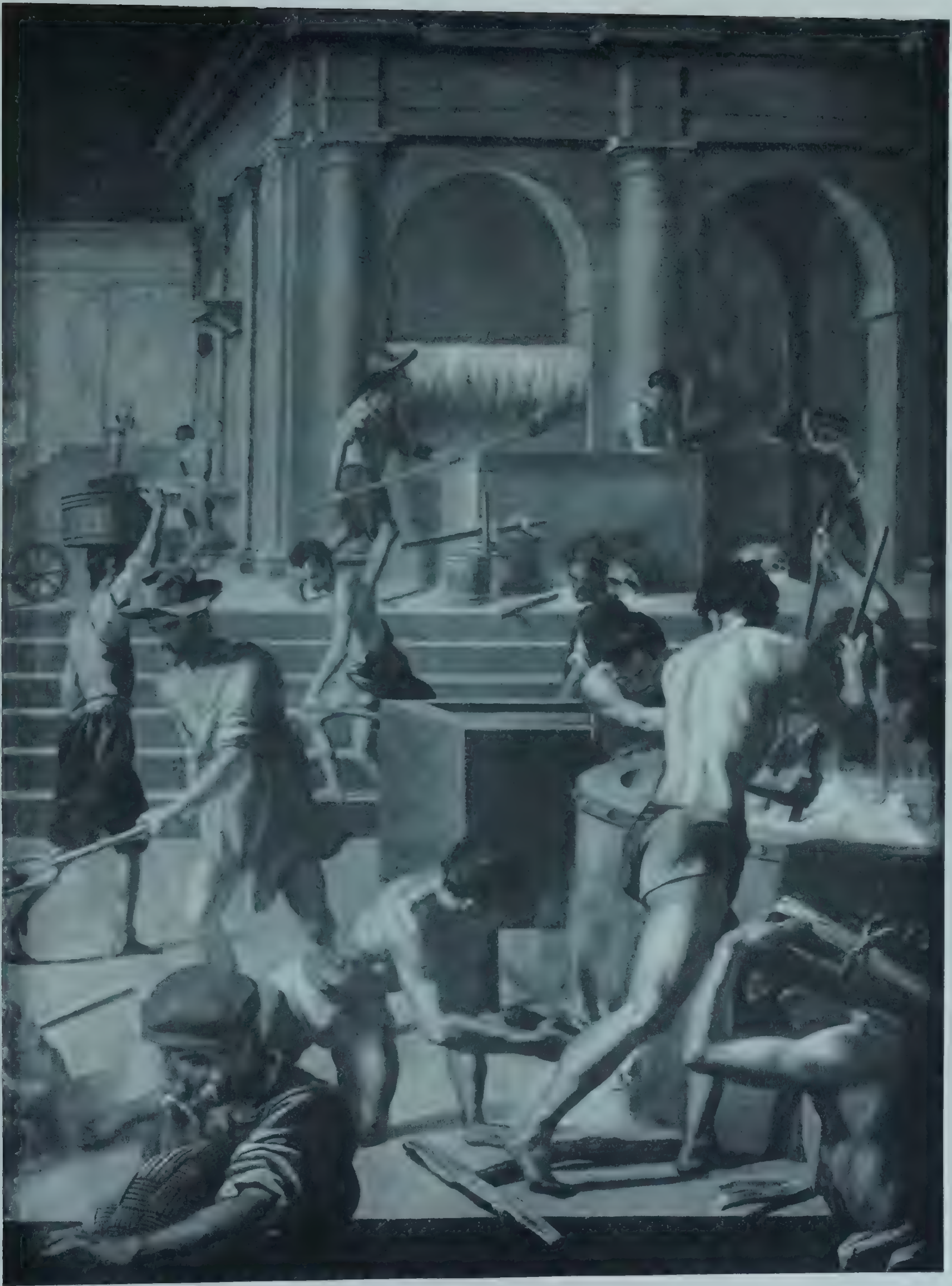
Alchemical laboratory. (Left) *Press for extracting juices;* (rear centre) *multiple still;* (foreground) *single still.* From the Studiolo *of Francesco I de' Medici* (1541–87), 1570. (pp 676, 707)



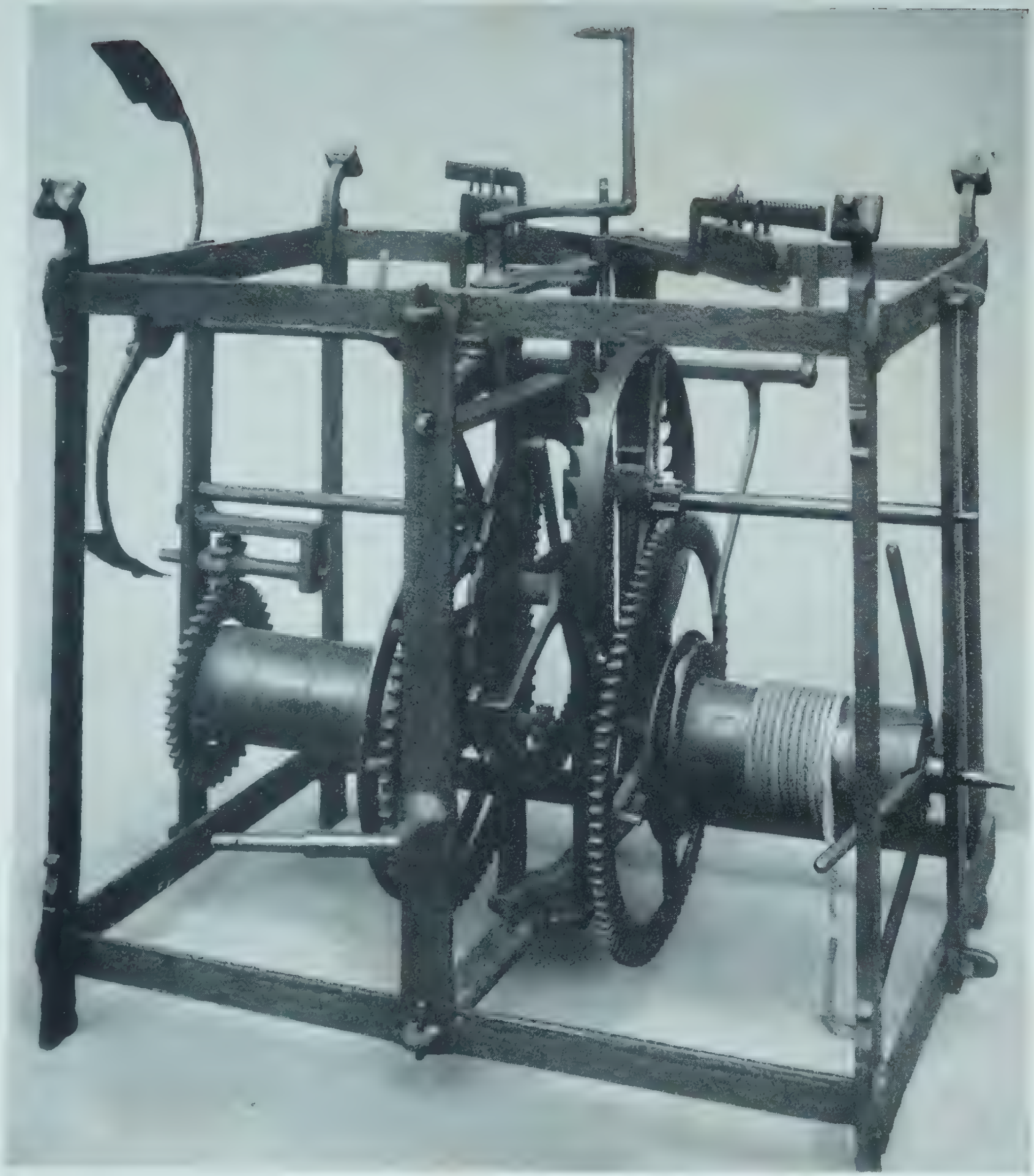
Jeweller's workshop. From the Studiolo *of Francesco I de' Medici,* c 1570. (pp 698, 707)



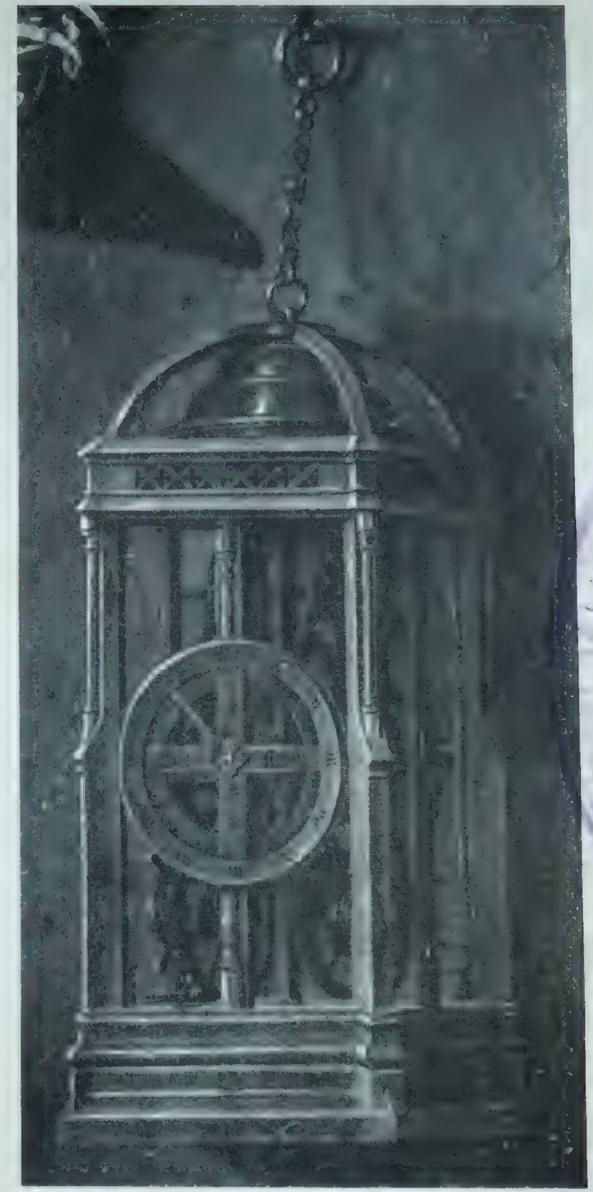
Painting by G. M. Butteri in the Studiolo *of Francesco I de' Medici,* c 1570, *showing a glass-works.* (Centre) *Pounding frit or 'tarso'*; (at rear) *blowing in a mould.* (pp 217, 678, 699, 707)



Dyers at work. In the right foreground the heated vat is lined with copper or lead. From the Studiolo *of Francesco I de' Medici*, c *1570*. (pp 702, 707)



A. An early turret-clock with going- and striking-trains, the well known Dover Castle clock. Although for many years wrongly ascribed to 1348, it is of the mid-seventeenth century. Its general lay-out is the same as that of the earliest clocks and it is one of the very few that have not been converted to pendulum control. (p 651)



B. *An early spring-driven clock from the background of a portrait of c 1440. Note the chain suspension indicating mobility, and the absence of weights. Note also the thumb-pieces for winding, similar to those in figure 392. The winding-key had not yet been invented.* (p 656)

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